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Hassnaa MOUSTAFA

Routage unicast et multicast dans les réseaux mobiles ad hoc

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Guy Pujolle	Université Pierre et Marie Curie	Président
David Simplot-Ryl	Université Lille1	Rapporteur
Nader Moayeri	NIST, USA	Rapporteur
Philippe Godlewski	ENST, Paris	Examinateur
Yvon Gourhand	France Télécom R&D	Examinateur
Olivier Marcé	Alcatel	Examinateur
Houda Labiod	ENST, Paris	Directeur de Thèse

S'il n'y avait pas d'hiver, le printemps ne serait pas si agréable: Si nous ne goûtions pas à l'adversité, la réussite ne serait pas tant appréciée

Anne Bradstreet

A ma mère,

mon mari Sami, et mon fils Noureldine

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Abstract

Mobile Ad hoc NETworks (MANETs), represent an emerging class of networks in which wireless mobile nodes operate independent of a backbone infrastructure. While hosts in traditional networks often rely on a designated router to forward data, every host in a MANET is required to route and forward data. The network hosts, such as laptops and personal digital assistants, operate on constrained battery power, and limited CPU and storage capacity. These networks suffer from scarce channel bandwidth resulting in throughput decrease, which decreases even further due to the effects of signal interference, and channel fading. Consequently, they rely on innovative network layer routing techniques to improve the reliability of the network, where specialized routing protocols are required, addressing some challenges such as the mobility of nodes and the resource constraints. Actually, most of the MANETs applications necessitate communication and coordination among a given set of nodes. Multicast routing protocols play an important role to provide this communication. It is always advantageous to use multicast rather than multiple unicast in the ad hoc environment, where bandwidth comes at a premium.

Our goal in this thesis is to propose new routing mechanisms and protocols, in the context of unicast and multicast routing, satisfying several requirements such as robustness, efficiency, adaptability, and energy consumption. Our first contribution in this thesis addresses the unicast routing via proposing a routing mechanism that is adaptive to the frequent change in topology as well as the nodes' battery power constraint. Our mechanism, named Energy Conserving Dynamic Source Routing (EC-DSR), modifies the Dynamic Source Routing (DSR) protocol taking into consideration the neighbors stability as well as the energy consumption during the paths' construction.

We also tackle the problem of providing efficient multicast routing in ad hoc networks. In this context, we propose a new mesh-based multicast routing protocol, named Source Routing-based Multicast Protocol (SRMP). SRMP uses the source routing concept and provides stable links with strong connectivity. In our approach, we address the connectivity quality concept in order to provide robustness, efficiency, and energy conserving.

Subsequently, we studied the performance evaluation of our propositions. We carried out our performance evaluation through simulations (under *ns*-2). Firstly, we implemented our unicast mechanism and compared its performance with DSR. Then we implemented our proposed multicast protocol and compared its performance with On-demand Multicast Routing Protocol (ODMRP) and Adaptive Demand-driven Multicast Routing (ADMR) protocol. We considered different mobility models in our performance evaluation, trying to provide a realistic ad hoc environment. We also

considered several mobility types and network configurations. Our obtained results demonstrate the efficiency of our propositions in terms of energy conserving, bandwidth utilization, and connectivity strength.

Finally, we derived an analytical model for our proposed Source Routing-based Multicast Protocol (SRMP). This model is investigated from the random graph theory, exploiting phase transition behavior from the percolation theory. Our results in this context, demonstrate the phase transition behavior for some routing characteristics, especially those concerned with the connectivity.

Résumé

I. Introduction

Le sujet de cette thèse se situe au cœur de la problématique posée actuellement dans le contexte des réseaux mobiles et plus précisément les réseaux ad hoc. Les problèmes de recherche qui y sont traités sont des problèmes ouverts et suscitent beaucoup d'intérêt de la part des organismes de normalisation (IETF, ….). Le routage dans ce type de réseaux est un problème qui n'est pas encore résolu. Les études courantes consistent principalement à proposer plusieurs solutions dans le cadre du routage ad hoc unicast. Ces mécanismes doivent être adaptés aux changements fréquents de la topologie, ainsi qu'à la durée limitative de la consommation d'énergie des nœuds du réseau.

Par ailleurs, peu de protocoles de routage multicast pour les réseaux ad-hoc ont été proposés. Pour fournir un routage multicast efficace dans les réseaux ad hoc, de nouveaux protocoles doivent être conçus. Ces protocoles devraient modifier la structure d'arbre multicast, ou déployer une topologie différente entre les membres des groupes multicast. Concevoir des protocoles de routage multicast est un problème complexe. La constitution du groupe peut changer, et la topologie du réseau peut également évoluer (les liens et les nœuds peuvent apparaître/disparaître). Les protocoles de routage doivent aussi considérer la durée limitée des batteries des équipements mobiles ainsi que leurs ressources limitée. Les objectifs à atteindre sont principalement: minimiser la charge du réseau, établir des routes optimales, minimiser la consommation d'énergie, assurer la fiabilité, l'efficacité et la mobilité illimitée.

Le but de cette thèse est donc de mettre en œuvre de nouveaux protocoles de routage unicast et multicast qui doivent répondre à plusieurs exigences : robustesse, efficacité, adaptabilité, optimisation de la consommation d'énergie, mobilité et qualité de la connectivité.

Dans ce résumé, nous essayerons de mettre l'accent sur les principes de base de nos travaux de recherche et les majeurs résultants et conclusions obtenus durant la thèse.

II. Problématique étudiée

Nos travaux se focalisent sur le routage réactif (on-demand), qui semble être plus approprié dans certains configuration de réseaux ad hoc où moins de ressources des réseaux sont consommées comparées à l'approche proactive surtout dans le cas d'un routage multicast.

Nous commençons par étudier les problématiques des routages unicast et multicast. Nous observons que l'interface radio ainsi que la mobilité des nœuds constituent des paramètres très pertinents à prendre en considération. Un troisième problème concerne la limitation des ressources (puissance, mémoire, CPU, …). Par conséquent, il est nécessaire de développer des protocoles puissants et efficaces qui assurent la bonne réception sur le canal radio et qui s'adaptent à ces problèmes critiques. Les protocoles de routage jouent un rôle très important et ont un impact considérable sur les performances.

Actuellement, les protocoles de routage des réseaux fixes ne sont pas appropriés et des nouveaux protocoles qui puissent s'adapter aux caractéristiques spéciales et aux diverses contraintes des réseaux ad hoc sont nécessaires. Des nombreuses propositions sont explorées dans le cadre du routage unicast, par contre peu de propositions ont étudié la problématique des réseaux multicast.

Malgré l'émergence de nombreuses applications dans les réseaux mobiles ad hoc qui nécessitent des communications multicast, tel que la visio-conférence, le travail de collaboration, et les jeux distribués, le multicast demeure toujours un problème complexe dans les réseaux ad hoc. La source multicast ainsi que les récepteurs sont mobiles, ceci augmente la complexité du problème. Malheureusement, les protocoles de routage multicast utilisés dans les réseaux fixes ne sont pas appropriés dans cet environnement dynamique. De plus, l'arbre multicast est fragile et demande beaucoup de re-configuration en fonction de la mobilité des nœuds qui est imprévisible. Ceci augmente l'échange des messages de contrôle, ce qui consomme beaucoup de ressources. Nous concluons qu'une stratégie différente, qui modifie la structure de l'arbre multicast, doit être appliquée au routage multicast ad hoc.

Nous considérons le routage unicast ainsi que le routage multicast. Dans ce cadre, nous étudions quelques caractéristiques afin d'améliorer la performance du routage. Plus précisément, nous étudions deux critères pour fournir des communications fiables: l'efficacité dans la consommation d'énergie et la qualité de connectivité. Ceci nous permet de traiter le problème de la consommation d'énergie dans les équipement mobiles qui est un défi pour la durée de vie du réseau, ainsi que le problème de non fiabilité des liens sans fil qui joue un rôle très important sur la réception de l'information

III. Contributions

Nous présentons trois contributions dans cette thèse: la première contribution concerne les travaux qui portent sur le routage unicast, la deuxième contribution traite des problèmes liés au routage multicast et finalement nous présentons dans la troisième contribution un modèle analytique basé sur la théorie des graphes aléatoires qui modélise le comportement de routage multicast dans les réseaux ad hoc.

III.1 Routage Unicast

La première contribution dans cette thèse concerne le routage unicast. Tout d'abord, nous avons étudié l'impact du modèle de mobilité sur la performance du routage des réseaux ad hoc. Nous avons développé un modèle de mobilité pour un réseau utilisant des robots (*Robot-Based*), appelé *Robot-based Mobility Patterns* (RMP), pour émuler des environnements de conférences ou de réunions interactives. De plus, nous avons proposé un mécanisme de routage qui s'adapte aux changements fréquents de topologie et qui optimise la consommation d'énergie. Ce mécanisme, appelé *Energy Conserving Dynamic Source Routing* (EC-DSR) [Mou03], étend le protocole de routage *Dynamic Source Routing* (DSR) [Joh96] en considérant plusieurs critères pertinents liés au contexte spécifique des réseaux ad hoc.

III.1.1 Modèle de Mobilité RMP

L'objectif de ce modèle de mobilité consiste à émuler les mouvements entre les participants à une conférence en utilisant un réseau mobile ad hoc pour fournir quelques services. Ce travail était réalisé dans le cadre du projet « Ambience ITEA » dans le but de modéliser l'environnement de conférences ou des réunions de travail. Nous avons considéré un ensemble de modèles de mobilité afin de modéliser les divers mouvements de participants. Ceci est utile aux applications qui incluent un système de gestion ou *Host Management Server* (HMS) dans lequel un serveur est responsable de fournir quelques services utiles à chaque participant, comme l'inscription automatique, un guide pour trouver ou localiser la salle de réunion, une connection Internet, et divers types de transmissions de données pendant une conférence ou une réunion.

Le modèle RMP est basé sur l'existence d'un groupe de nœuds robots qui permettent à chaque participant d'accéder à un ensemble de services. Ces robots communiquent ensemble pour offrir tous les types de transmission de données entre les participants et serveur HMS. Il est supposé que chaque participant est un nœud ad hoc, équipé avec un PDA (*Personal Digital Assistant*) ou un PC portable. De plus, le serveur HMS est capable de se connecter à l'Internet et de stocker toutes les informations nécessaires concernant l'inscription des participants, les réunions et les diverses bases de données.

Nous avons implémenté ce modèle sous *ns*-2 et nous avons évalué son impact sur la performance du protocole de routage DSR en utilisant des scénarii de trafics différents. Le but était d'évaluer les performances du routage ad hoc avec divers mouvement de nœuds Le protocole de routage DSR a été testé avec le modèle de mobilité RMP en utilisant deux types de trafics:

- Un trafic CBR (*Constant Bit Rate*): taille de paquet = 512 octets, taux de transmission = 4 paquets/seconde, et nombre maximum de paquets = 3000;
- Un trafic VBR (V*ariable Bit Rate*): Vidéo, H. 263 encoding.

Nous avons étudié l'impact de ce modèle de mobilité sur la fiabilité des communications. La fiabilité des communication est définie par la continuité de connectivité entre les robots ainsi que entre chaque nœud participant et le serveur HMS en utilisant au moins un robot. Les métriques de performance utilisées sont le nombre des échecs de connectivité (*Connectivity Failures*) et le taux des échecs de connectivité. Les résultants obtenus montrent que DSR est plus robuste avec le trafic CBR comparé au trafic vidéo. De plus, les comportements de routage changent selon chaque type de mouvements dans ce modèle.

III.1.2 Protocole de routage EC-DSR

Dans cette partie, nous proposons un mécanisme de routage unicast qui s'adapte aux changements fréquents de topologie et qui améliore la durée de vie des batteries. Ce mécanisme, appelé *Energy Conserving Dynamic Source Routing* (EC-DSR), modifie le protocole DSR en considérant la stabilité des nœuds voisins ainsi que la consommation d'énergie pendant la construction des chemins.

L'objectif est de fournir des nouvelles caractéristiques de routage qui permettent une utilisation efficace de la bande passante et assure une consommation d'énergie minimum sur les chemins construits. EC-DSR minimise la charge du réseau en optimisant l'utilisation des ressources. Les mécanismes de EC-DSR peuvent être appliqués à n'importe quel protocole de routage réactif qui comporte une phase de découverte des chemins. Dans le cadre de cette thèse, ils sont appliqués du protocole DSR en modifiant sa phase de découverte et en ajoutant une nouvelle structure de données pour stocker les informations de stabilité et de qualité parmi les voisins.

Pendant la construction des chemins, une phase de sélection de nœuds est employée pour choisir les nœuds les plus stables qui consomment moins d'énergie et qui fourni une bonne qualité de liens. Les nœuds sont choisis selon quatre critères: le niveau de batterie, la stabilité de nœuds par rapport à chaque voisin, la qualité de lien selon la puissance des signaux transmis et la disponibilité des liens. Au moment où nous avons établi notre proposition la plupart des protocoles de routage existants employaient seulement une métrique pour le choix des chemins. En effet, EC-DSR a une approche adaptative qui minimise la consommation d'énergie parmi les nœuds de chaque chemin. Nous avons défini un nouveau concept qui est celui de la qualité de connectivité pendant la sélection des nœuds. Ceci est fait en utilisant les informations de stabilité des voisins, la conservation d'énergie, la disponibilité et la qualité des liens.

III.1.3 Etude de performance du protocole EC-DSR

Afin d'évaluer les performances du protocole EC-DSR, nous l'avons implémenté sous le simulateur ns-2. Une étude comparative est aussi menée pour comparer EC-DSR au protocole DSR et pour montrer l'amélioration attendue de EC-DSR.

L'évaluation des performances de EC-DSR montre une réduction importante des messages de contrôle comparés à DSR dans un réseau relativement petit [Mou03b]. De plus, le débit est amélioré ainsi que la taux de perte de paquets de donnée. Ces résultats montrent l'efficacité de EC-DSR et sa robustesse dans ce type de configuration. Dans un réseau supportant un nombre important de nœuds, EC-DSR se montre plus efficace comparés à DSR quand la charge du trafic augmente [Mou03a].

Une autre évaluation de performance est effectuée pour étudier l'impact du modèle de mobilité sur les performances de EC-DSR [Mou05]. Trois modèles de mobilité sont utilisés dans cette étude: le modèle de *RandomWay Point* (RWP), le modèle de *Pursue* (PM) et le modèle de *Reference Point Group Mobility* (RPGM). Ceci permet d'analyser la performance en utilisant des mouvements aléatoires ainsi que des mouvements en groupe. Les résultats dans cette partie montrent que EC-DSR est plus efficace avec les modèles PM et RPGM qui sont des modèles de mobilité groupée.

De plus, EC-DSR montre de meilleurs résultats avec le modèle PM en terme de débit, de délai et de taux d'échec des liens. Ces résultats sont obtenus en faisant varier la vitesse de déplacement des nœuds. Par contre, en terme de consommation d'énergie, EC-DSR ne montre pas de bons résultats avec le modèle PM par rapport aux autres modèles RWP et RPGM. En fait, le modèle PM offre des mouvements très corrélés des nœuds qui mène à la construction de chemins plus stables par rapport aux deux autres modèles, RWP et RPGM. Ceci pose plus de charge sur les nœuds et donc consomme plus d'énergie.

En conclusion générale, EC-DSR est plus robuste et efficace avec les modèles de mobilité de groupe surtout dans des configurations de réseaux plus grandes.

III.2 Routage multicast

La deuxième partie de notre travail a consisté à étudier le problème du routage multicast dans les réseaux ad hoc. A la suite d'une analyse des protocoles de routage multicast utilisés dans les réseaux fixe, nous avons conclu que ces derniers étaient inappropriés dans le cas des réseaux ad hoc.

A cause des reconfigurations fréquentes à cause de la dynamicité de l'environnement des réseaux ad hoc, la plupart des protocoles multicast peuvent difficilement maintenir la structure de l'arbre multicast en utilisant plus de messages de contrôle qui consomment plus de ressources. Ces protocoles nécessitent aussi plus de capacité de stockage puisque ils exploitent des informations des nœuds montants et des nœuds descendants. Généralement, le critère choisi lors du choix de la route est le critère du plus court chemin, qui s'avoie inapproprié aux changements fréquents et imprévisibles de la topologie du réseau.

Dans le but de fournir un routage multicast efficace consommant moins de ressources, nous avons proposé un nouveau protocole de routage multicast, appelé *Source Routing-based Multicast Protocol* (SRMP) [Mou04]. Ce protocole utilise le concept de routage à la source « source routing ». SRMP permet d'assurer une connectivité élevée ainsi qu'une stabilité des liens entre les nœuds tout en minimisant la consommation d'énergie.

SRMP est un protocole de type « mesh-based » qui modifie la structure fragile de l'arbre multicast. C'est un protocole réactif qui minimise les messages de contrôle ainsi que la consommation des ressources (mémoire, CPU, batterie, …). Une topologie maillée est construite entre les membres du groupe multicast pour fournir plus de connectivité. Ceci a plusieurs avantages par rapport à la topologie d'arbre: plusieurs chemins sont fournis entre les membres de groupe, ce qui permet plus de robustesse dans un environnement variable. Les inconvénients liés à la structure d'arbre multicast comme la concentration de trafic et la reconfiguration fréquente en cas de changement de topologie sont ainsi éliminés.

SRMP utilise le concept de nœuds FG (*Forwarding Group*) pendant la construction de sa topologie maillée, où un ensemble de nœuds sont choisis parmi les nœuds du réseau pour transférer les paquets de données. Ce concept minimise la taille de diffusion et donc optimise l'utilisation des ressources ainsi que la charge de réseau.

Le choix des nœuds FG a un impact direct sur la qualité de connectivité. Une approche efficace est employée pour sélectionner les nœuds FG, ceci permet la construction d'une topologie maillée robuste qui fournit une bonne qualité de connectivité. Cette approche se base sur l'utilisation de quatre métriques pendant la phase d'établissement de chaque lien:

- La disponibilité de lien selon un modèle de prédiction [Jia01] qui donne une probabilité de disponibilité de lien au moment T_1 étant donné que le lien est disponible au moment T_0. Un lien est considéré disponible si sa qualité radio répond à certaines exigences pour une bonne communication;
- La stabilité du chemin où chaque nœud est stable vis-à-vis de ses voisins;
- La puissance du signal émis sur les liens;
- Le niveau élevé de batterie où les nœuds choisis devraient consommer moins d'énergie.

Cette approche étant basée sur des «métriques multiples», où chaque métrique est validée en utilisant un seuil, nous avons également effectué une étude adaptative pour le choix des seuils de ces métriques.

Le protocole SRMP utilise des mécanismes de maintenance pour la mise à jour d'information entre chaque nœud et ses voisins, la mise à jours des chemins de la structure maillée, la reconfiguration de cette structure, et l'élagage des nœuds.

La mise à jour d'information des voisins au niveau de chaque nœud est effectuée en utilisant les messages balise «*Beacon*» de la couche MAC. Quand un nœud reçoit un *Beacon* d'un voisin, il met à jour ses informations vers ce voisin concernant la puissance du signal, le niveau de stabilité et la disponibilité de lien. La mise à jour des chemins est effectuée pendant la transmission des paquets de données. La reconfiguration de la structure maillée est effectuée en se basant sur la couche MAC qui détecte les échecs des liens, puis des mécanismes de réparation des liens peuvent êtres effectués entre chaque deux nœuds FG ainsi que entre un nœuds FG et un membre de groupe multicast. Les mécanismes d'élagage permettent à un nœud de quitter le groupe multicast au cas d'une source qui a terminé ses transmissions, un récepteur qui ne veut plus recevoir de données, ou un nœud FG qui ne veut plus participer à la transmission/routage.

III.2.1 Etude de performance du protocole SRMP

Afin d'évaluer les performances de SRMP, nous l'avons implémenté sous le simulateur *ns*-2. De plus, une étude comparative a été menée qui a comparé SRMP à deux autre protocoles multicast: ODMRP (*On-demand Multicast Routing Protocol*) et ADMR (*Adaptive Demand-driven Multicast Routing*). Les résultats obtenus sont favorables pour SRMP dans plusieurs aspects. Plusieurs modèles de mobilité ont été également étudiés. L'effet de changement du type de mobilité, des configurations de réseau, et de la composition de groupes multicast sur la performance de chaque protocole a été finement analysé.

Une étude approfondie d'évaluation de performances a été réalisée dans laquelle plusieurs scénarii de mobilité et de communication ont été étudiés. Nous avons aussi employé dans cette évaluation diverses configurations des réseaux, divers modèles de mobilité et diverses compositions des groupes multicast. Une étude de performance par rapport aux deux protocoles ODMRP [Lee00b] et ADMR [Jet01a] a été également effectuée. ODMRP est un des premiers protocoles multicast «mesh-based » qui a montré de bons résultats. ADMR est un des principaux protocoles multicast «tree-based».

Les résultants obtenus montrent des différences malgré que les trois protocoles sont réactifs et malgré que SRMP et ODMRP sont des protocoles de type mesh. L'analyse de ces protocoles montre que SRMP a de meilleurs débits dans les réseaux de 20 nœuds à faible mobilité et les réseaux de 30 nœuds de mobilité moyenne. Dans des configurations plus grandes, le débit atteint 100% avec un seul groupe multicast. Dans le cas de forte mobilité, SRMP montre une amélioration 75% à 80% de débit par rapport à ODMRP et ADMR. Concernant le délai, SRMP montre un délai qui diminue en cas de mobilité dans des réseaux de 20 nœuds et un délai constant dans des réseaux de 30 nœuds.

Grâce au concept de la qualité de connectivité employé dans SRMP, le nombre de re-transmissions de données, dans la couche MAC, est largement inférieur à ODMRP et ADMR. Ceci permet à SRMP de mieux utiliser la bande passante et de fournir un routage multicast efficace. Notons aussi que le nombre d'échecs de liens diminue quand la taille de groupes multicast est petit, et la robustesse du protocole augmente en forte mobilité grâce à la construction de la structure maillée avec des chemins plus récents.

A cause des ressources d’énergie limitées dans les nœuds ad hoc, la consommation d’énergie est très pertinente. Pour cela, une évaluation de performance en terme de consommation d‘énergie est effectuée en considérant des réseaux plus grands. Les résultats obtenus montrent l’impact de la composition du groupe multicast sur la consommation, surtout quand le nombre de récepteurs multicast change. Il est aussi noté que la consommation d’énergie a un impact sur la durée de vie des liens et donc sur la fiabilité de la structure globale de routage.

En étudiant l’effet du modèle de mobilité sur la performance, SRMP a obtenu de meilleurs résultats avec les modèles de mobilité de groupe surtout quand la taille du groupe multicast augmente.

III.2.2 Etude des seuils pour le choix des métriques par les nœuds «FG»

A cause de l’application de «métriques multiples» pendant la construction de la structure de routage, nous avons effectué une étude pour analyser les seuils utilisés dans le processus de sélection de nœuds «FG». Ce processus a lieu dans la phase de découverte des chemins de la structure maillée ainsi que dans la phase de sa re-configuration. Le but de cette étude est de déclarer l’existence d’un ensemble approprié de seuils qui doivent être adaptatifs à la configuration des réseaux et au type de mobilité.

Cette étude est basée sur la simulation, où plusieurs ‘cas de test’ avec divers valeurs de seuils sont utilisés. La performance de SRMP est analysée avec chaque ‘cas de test’ pour étudier l’impact de changement de valeurs de seuils sur la performance du protocole.

Nous avons abouti à la conclusion qu’il est impératif d’utiliser des seuils adaptatifs qui accompagnent l’évolution de l’environnement du réseau.

III.3 Modéle analytique RRG

Dans une troisième phase, nous avons étudié SRMP d’un point de vue analytique. En fait, les graphes aléatoires sont bien adaptés pour modéliser un réseau de topologie complexe comme un réseau ad hoc. Dans ce cadre, nous avons dérivé un modèle analytique afin de modéliser SRMP et d’analyser le comportement de ses caractéristiques, surtout celles qui concernent la connectivité. Ce nouveau modèle, appelé RRG (*Reactive Random Graphe*), est élaboré basé sur la théorie des graphes aléatoires.

Plus précisément, nous avons modélisé la topologie maillée qui est construite à la demande considérant diverses contraintes de l'environnement radio.

A cause de la complexité du problème de routage dans les réseaux ad hoc, peu de contributions ont étudié les caractéristiques des protocoles de routage unicast d'un point de vue analytique. Le modèle RRG constitue un des premiers modèles analytiques qui modélisent un protocole de routage multicast dans un réseau ad hoc.

Ce modèle, modélise la topologie de maille comme un graphe de communications aléatoires. Ce graphe réactif est seulement construit à la demande lorsque la source de groupe Multicast a des paquets de données à envoyer pour le groupe. De plus, ce modèle considère un environnement radio réaliste qui permet la construction de lien d'une façon réactive, selon la qualité radio entre chaque paire de nœuds.

Les résultats numériques de ce modèle montrent un comportement de transition de phase pour certaines propriétés de SRMP, particulièrement celles qui concernent la connectivité. De plus, quelques propriétés intéressantes sont montrées qui aident à ajuster la taille de maille en terme de nombre des liens selon le nombre de nœuds *N* du graphe. Nous avons noté que les récepteurs de groupe multicast sont presque connectés si le nombre des liens de la maille (graphe) est supérieur ou égal à *NlogN/2*, ainsi le degré moyen de graphe est supérieur à *ln(N)*. Ces résultats concordent parfaitement aux autres résultats et théorèmes principaux de la théorie des graphes aléatoires [Fra95, Alb02].

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CHAPTER 1 INTRODUCTION

The advent of ubiquitous computing and the proliferation of portable computing devices have raised the importance of mobile and wireless networking. Mobile Ad hoc NETworks (MANETs) are specific network configurations that appear in the context of these networks. They provide a powerful paradigm for modeling self-configuring wireless networks which make them so appropriate to use in the fourth generation of mobile networks. In the recent years, ad hoc networks recognize a significant explosion of activities due to their ease of deployment in response to some application needs together with the availability of low cost peripherals (laptops, palmtops) equipped with wireless interfaces.

1.1 Background and Motivation

Ad hoc wireless networks have emerged as a category of wireless networks that utilize multi-hop radio relays and are capable of operating in a self-organizing and self-configuring manner without the support of any fixed infrastructure. The principle behind ad hoc networking is multi-hop relaying, which was studied in the past under the name of packet radio networks (PRNET) in relation to defense research carried by the defense advanced research projects agency (DARPA) in the early 1970s [Dar04]. During the 1980s, research on military applications was extensively funded across the globe. Realizing the necessity of open standards in this emerging area of computer communication, a working group within the Internet Engineering Task Force (IETF), the mobile ad hoc networks (MANET) working group [Iet04], was formed to standardize the IP-based protocols and functional specifications of ad hoc wireless networks. The vision of the IETF effort in the MANET working group is to provide improved standardized routing functionality to support self-organizing mobile networking infrastructure.

A MANET is an autonomous collection of mobile nodes communicating over wireless links. Users can communicate with each other in a temporary manner with no centralized administration and in a dynamic topology that changes frequently. A MANET is best described as an infrastructureless network, in which mobile nodes dynamically organize themselves and establish routes among themselves *on the fly* [Bro98]. Each mobile node acts both as a host and as a router and must therefore be willing to forward packets for other networks' nodes.

Ad hoc networks possess some interesting features that do not exist in cellular networks. Due to the lack of infrastructure and the unconstrained connectivity, they can be setup on demand, and can handle the rapid and unpredicted topology changes. Moreover, they are fault tolerant networks handling any malfunctions due to nodes movements, while maintaining the network operational. This takes place through network re-configurations carried out by efficient routing protocols.

Due to the quick and economical deployment of ad hoc networks, they found applications in several areas. They have been firstly used in military applications, including emergency rescue activities when the conventional infrastructure based communication facilities are destroyed due to a war, or earthquakes, or hurricanes. They are also used in residential zones providing an alternative communication infrastructure for mobile or fixed users along highways or in university campuses.

Like all wireless environments, radio links are not perfect and they are affected by several sources of error. Firstly, unidirectional links may exist in ad hoc networks, affecting the communication between any two nodes. Secondly, the *hidden node problem*, in which two transmitters could not hear each other and want to send to the same receiver, causes collision. Also the *exposed node problem*, in which nodes in the transmission range of the sender of an on-going session are prevented from making a transmission, reduces the bandwidth efficiency of the system [Mur04]. Furthermore, some types of constraints arise in ad hoc networks due to the nature of the radio channel. These networks are characterized by limited bandwidth, and signal attenuation is highly liable as a function of the covered distance. Interference may also take place due to signal attenuation, reflection or multiple paths. Other types of constraints come from the wireless equipments. Since mobile nodes are mainly small size devices, they are "thin clients" having limited CPU capacity, storage capacity and battery power. This imposes certain restrictions on the power and resources usage.

Consequently, one of the critical issues of a MANET is its radio interface. The second one is ***the mobility of the nodes***. A third and important issue is ***the limited equipments' resources***, including power and storage capacity. Therefore, it is necessary to develop powerful protocols that ensure a correct reception of transmitted information on radio links, and can adapt to the nodes' mobility together with the resources' limitations. Among these protocols, those related to routing play a very significant role in the performance of these networks. For this purpose, routing protocols used in wired networks are not appropriate and there is a need for new routing protocols, adapting to the special nature and various constraints of ad hoc networks.

1.2 Problem Statement: Routing Challenges and Multicast Interest

Unlike typical wired networks protocols, routing is extremely challenging in ad hoc networks and the routing protocols must address a diverse range of issues. Since the network topology can change rapidly at unpredictable times, the routing protocols should be efficient in re-configuring the network and repairing the broken paths, coping with the nodes mobility and providing fault tolerance capability. Also, since wireless links generally have lower bandwidth, the routing protocols should be efficient in bandwidth utilization, through minimizing the control messages overhead.

Beside bandwidth issues, the majority of nodes in ad hoc networks are “thin-clients” relying on exhaustible batteries, thus routing protocols should minimize the energy consumption to increase the network lifetime. Moreover, due to the nature of the wireless medium, the routing protocols should allow links with higher quality coping with signals attenuation and interference which may take place. To summarize, a fundamental challenge in the design of ad hoc networks is the development of routing protocols fulfilling some key features like robustness, simplicity, quality of connectivity and energy conserving.

Multicast routing appears to be a key issue in ad hoc networks, since there are more and more ad hoc applications where one-to-many dissemination is necessary. By extending multicast technology to the ad hoc domain, applications such as videoconferencing, distributed games and computer collaborative work can be provided with enhanced performance thanks to the optimization of network resources. The advantage in multicast communication is to provide efficient saving in bandwidth, and data delivery with highly unpredictable nodes’ mobility, and to reduce communication cost and network resources since the sender can transmit the data with a single transmission to a group of receivers. However, most MANETs do not support multicast communication, even though wireless links have a broadcasting nature suitable to such communication.

Although many unicast routing protocols have been explored, research involving multicast routing protocols is still limited. In general, wireless mobile multicasting poses several key challenges. Multicast sources move, making source oriented multicast protocols inefficient. Also, multicast group members move, thus preventing the use of a fixed multicast topology. In fact, the multicast communication mechanism of fixed static Internet environment is not suitable for multihop wireless environment used in multicast trees, which are fragile and difficult to maintain with respect to the unpredictable and rapid mobility. Besides, multicast trees usually require a global burdensome routing substructure such as link state or distance vector. This leads to frequent exchange of routing vectors or link state tables due to continuous topology change causing excessive channel and storage overhead.

Thus, ***multicast plays an important role in ad hoc networks*** and many issues have to be addressed. A ***key problem is to enable efficient multicast routing*** that requires the application of a different kind of routing strategy, modifying the conventional tree structure or deploying a different topology between group members such as the mesh topology.

From our study and investigation, we observed that ad hoc routing is a challenging research domain. Our work focuses on on-demand protocols. Previous studies [Lee00a] have shown that such protocols are better suited for ad hoc networks because they generate less control overhead and manage the mobility in a more efficient manner. In this context, we investigate some unicast and multicast routing characteristics to enhance the routing performance. More precisely, we are concerned with two key issues for providing reliable routing, which are power efficiency and connectivity quality. The former treats the problem of limited equipments power in ad hoc networks, which poses a significant challenge for nodes operation and the network lifetime. The latter treats the problem of unreliable wireless links and plays an important role in assuring correct reception at the receivers.

In our study, we achieve energy efficient routing through selecting paths in an energy conservative mean, according to the energy level at each node in the path. Additionally, routing with high quality of connectivity is achieved through selecting qualitative links during the construction of the routing paths. These links should guarantee a certain stability level between its end nodes. Also, they should have high signal strength, and higher expected lifetime.

1.3 Accomplishments and Contributions

Our work in this thesis concentrates on routing in ad hoc networks. More specifically, we focus on on-demand routing, which is particularly attractive in such dynamic networks where traffic overhead caused by routing updates may become prohibitive.

We tackle the unicast as well as the multicast routing. In the former, we treat the energy-conserving problem trying to optimize and conserve as much power as possible, since routing and power consumption are intrinsically connected, while still achieving good links quality. In the latter, we focus on providing reliable multicast routing that solves the routing problems in the multicast tree structure. Our approach in this issue utilizes the concept of connectivity quality, as a means of providing qualitative links between the multicast nodes, which is of great interest in an ad hoc environment.

Our contributions that are elaborated throughout this thesis are listed as follows:

- We investigated the impact of mobility models on the routing performance in ad hoc networks. In this subject, we developed a robot-based mobility model emulating conference-like applications. We implemented this model under *ns*-2 network simulator and evaluated its impact on the performance of DSR unicast routing protocol using different traffic scenarios.
- We studied the energy conserving unicast routing mechanisms, extracting their limitations and proposing new characteristics in unicast ad hoc routing to provide efficient saving in bandwidth and network resources. In this subject, we designed a unicast routing mechanism, named EC-DSR, to ensure minimum energy consumption along the different used routes. We implemented our mechanism under *ns*-2 network simulator, evaluating and analyzing its performance using different network configurations, traffic types and different mobility models. Also, we carried out a comparison study with the initial DSR protocol.
- We proposed the Source Routing-based Multicast Protocol (SRMP). SRMP is an on-demand mesh based protocol applying the concept of source routing during its mesh construction and exploiting a connectivity quality approach. SRMP minimizes the flooding size through developing four metrics for selecting the mesh members. The values of these metrics are decided according to predefined and adaptive thresholds. The mesh topology makes SRMP robust towards mobility, and the connectivity quality approach provides reliable communication.
- We implemented SRMP under *ns*-2 network simulator and studied and evaluated its performance using different network configurations, traffic scenarios, and mobility patterns. Also, we compared its performance with ADMR and ODMRP multicast routing protocols, illustrating the performance differences according to the mechanisms and category of each protocol.
- We carried out a study for the impact of the thresholds values on SRMP performance. Our goal is to provide an appropriate thresholds set that allows a robust mesh construction, and hence improves SRMP performance.
- Finally, we derived an analytical model for our proposed multicast protocol SRMP. This model is investigated from the random graph theory, exploiting the phase transition behavior from the percolation theory, and aims at validating some key features to improve SRMP performance. To our knowledge, this work is the first to propose an analytical model for a multicast routing protocol in ad hoc networks.

1.4 Organization of the Thesis

This thesis focuses on the on-demand unicast and multicast routing protocols design in ad hoc networks and their performance evaluation.

Chapter 2 explores through unicast routing in ad hoc networks, stating the unicast routing challenges, and the requirements for an efficient ad hoc unicast routing protocol. The different mobility models in ad hoc networks are also discussed, showing the impact of changing the mobility pattern on the routing performance, and presenting our robot based mobility patterns (RMP).

Chapter 3 studies the multicast routing problem in ad hoc networks, introducing the main challenges in the design of multicast routing protocols. It also classifies the existing multicast routing protocols and discusses some major examples of these protocols.

Chapter 4 provides an overview on power efficient routing techniques for ad hoc networks, highlighting new characteristics to provide efficient routing. It then presents our proposed energy conserving unicast routing mechanism (EC-DSR), evaluating its performance under different network configurations and mobility models, and comparing its performance with DSR protocol.

Chapter 5 introduces our proposed multicast routing protocol (SRMP), providing a detailed explanation of its mechanisms, operation, data structures, and maintenance approach. It then conducts a simulation performance evaluation of SRMP under different network configurations, traffic types, and mobility patterns. A full comparison study with ODMRP and ADMR is also provided.

Chapter 6 studies the thresholds' effect on the performance of SRMP, analyzing the protocol's behavior under several combinations of thresholds' values to extract an appropriate threshold set that allows robust mesh construction.

Chapter 7 proposes the reactive random graph (RRG) model in modeling SRMP, emphasizing its behavior and basic features.

Finally, **Chapter 8** concludes our thesis through giving a summary of the achieved work and discusses the directions for future research in this topic.

CHAPTER 2 UNICAST ROUTING IN AD HOC NETWORKS

Wireless communication and mobility in ad hoc networks, unlike traditional wired networks, require different types of routing protocols that should be based on new and different principles. Routing protocols for traditional wired networks are designed under the assumption that the nodes' relative positions generally remain unchanged and the links between them always exist. In a mobile ad hoc network, however, the topology changes so frequently as the mobile nodes move. Furthermore, links existence between neighbor nodes is not always assured due to the nature of the wireless medium, such as the presence of obstacles and unidirectional links.

In this chapter, we present a state of the art of some proposed unicast routing protocols in ad hoc networks. These routing protocols belong to several classifications based on when and how the routes are discovered.

In the following sections, we discuss existing conventional routing protocols in wired networks and the properties and limitations that make them inappropriate in mobile ad hoc networks. Then we present different proposed ad hoc routing protocols, discussing their advantages and limitations. Finally, we illustrate the mobility models impact on ad hoc routing and we propose a robot based mobility model suitable for conference like applications.

2.1 Conventional Routing Protocols Limitation in Ad hoc Networks

In ad hoc networks, it is almost necessary to traverse several hops (multi-hops) before a packet reaches the destination. In traditional hop-by-hop routing solutions, each node in the network maintains a routing table that lists, for each known destination, the next node to which a packet for that destination should be sent. The problem of maintaining consistent and correct tables becomes harder in ad hoc networks, due to the high rate of topology changes.

The challenge in creating a routing protocol for ad hoc networks is to design a single protocol that can adapt to the wide variety of conditions that are present in any ad hoc network over time. As ad hoc networks are characterized by a time-changing topology, use of wireless medium, and limited bandwidth and power, there is a need to develop new different routing protocols than those for wired networks. Actually, a central challenge in the design of ad hoc networks is the development of dynamic routing protocols that can efficiently find routes between two communicating nodes. The routing protocols must be able to keep up with the high degree of node mobility, the absence of established infrastructure, the absence of a centralized administration, the bandwidth and resources constraints.

Wired networks routing protocols are designed for static topology, they try to maintain routes to all reachable destinations, and they are highly dependent on periodic control messages. These protocols are mainly classified into link state and distance vector protocols, requiring frequent exchange of link state tables or routing vectors. These routing types cause excessive channel and processing overhead in ad hoc networks, due to the limited bandwidth and processing and storage capacity. In addition, pure distance vector algorithms, as Distributed Bellman Ford (DBF) [Per94], do not perform well in mobile networks because of slow convergence and counting to infinity problem [Lee00a].

Thus, the traditional wired network protocols consume more resources such as bandwidth, battery power, and CPU, and hence they are not appropriate in ad hoc networks where all transmissions and updates are transmitted over air, and which rely on devices (Laptops, PDA) that heavily depend on battery lifetime. Moreover, they assume bi-directional links, which is not always the case in a wireless radio environment.

Accordingly, new routing protocols are required facing some major challenges, like the mobility of nodes and the resource constraints. The major routing requirements are the following [Mur04]:

- **Distributed operation:** the protocols must be fully distributed, providing scalability and fault tolerance;
- **Loop freedom**: the protocols must be free from loops as well as stale routes;
- **Minimum control overhead**: the control packets in a routing protocol should be kept as minimum as possible, as they consume precious bandwidth and can cause collisions with data packets, reducing the throughput;
- **Scalability**: the protocols should be able to scale well in a network of large number of nodes. This requires minimization of the control overhead;
- **Resource conservation**: the protocols should optimize the use of the scarce resources such as bandwidth, computing power, memory, and CPU;

- **Unidirectional link support**: the protocols must support the existence of unidirectional link, which is highly liable in a wireless radio environment;
- **Multiple routes**: because of frequent link failures, the protocols should provide more than one route to the destination to guarantee robust communication and delivery in such a highly dynamic environment;
- **Security and privacy**: the protocols must be resilient to threats and vulnerabilities, through built-in capabilities that prevent any possible attacks against an ad hoc network and avoid denial of service and aggressive resources consumption;
- **Quality of service**: the protocols should be able to provide a certain level of quality of service (QoS) as demanded by the applications.

However, none of the proposed protocols comprises all the desired properties, but rather these protocols are still under development and are probably extending with more functionality. For this purpose, the MANET working group [Iet04] has been formed within the IETF to develop a routing framework for routing protocols in ad hoc networks.

2.2 Different Routing Approaches

Routing protocols in ad hoc networks may be classified either according to their routing approach, their routing architecture or their communication reliability. Figure 2.1 shows these three different classifications for major existing routing protocols.

2.2.1 The Broad General Classification

A large number of protocols include a periodic behavior, these protocols regularly perform some operations in a periodic manner, using periodic control messages, for the whole network lifetime. The idea behind this behavior is to continuously maintain the routes within the network, so that when a packet needs to be forwarded, the route is already known and can be immediately used. These types of protocols are known as **proactive or table-driven** protocols. The alternative to this approach is the **reactive or on-demand** protocols, which invoke a route determination procedure only on-demand. Thus, when a route is needed, a route discovery procedure is applied based mainly on query-reply exchanges. A **hybrid** approach comes in between, where the routing protocol view the network as a group of zones, applying a proactive approach within each zone while using a reactive approach between the zones in order to discover the routes to the outside nodes.

This is a broad general classification for routing protocols in ad hoc networks, where it is based on the route establishment mechanism. We notice that, routes can be quickly established in proactive scheme, since when a route is needed, the delay before the actual packets sent is very small. The reactive scheme takes a lazy approach, in which routes are only created when desired by the source node, in an on-demand fashion. In this case, the initial search latency may impact the performance of interactive applications (e.g. distributed database query). Another type of limitation arises in applications requiring QoS guarantees such as multimedia traffic scenarios. With on-demand route discovery, it is impossible to know in advance the quality of the path (e.g. bandwidth, delay, etc) prior to call setup. Such a priori knowledge, which can be easily obtained from proactive schemes, is very desirable in such applications, as it enables effective call acceptance control. The proactive protocols attempt to continuously find routes between all source-destination pairs regardless of the use or need for such routes, which results in a waste of network capacity especially if the topology changes are more frequent than the rate of tables updates. On the other hand, the on-demand scheme comes with a key motivation to reduce the routing load especially in highly dynamic networks topology, where all up-to-dates routes are not maintained at every node and nodes initiate route discovery only when they need to send packets to specific destination.

The hybrid approach comes as a compromise between proactive and reactive schemes. The main idea is to allow the routing protocols to initiate the route determination procedure on-demand, but at limited search cost. In such types of protocols, each node maintains the topology information within its zone (coverage area) in a proactive approach using an arbitrary proactive routing scheme, while it discovers the route on-demand, using a reactive algorithm, for any node outside its zone. The expected advantage from this approach is the scalability improvements, where routing tables sizes would be equal to the zone size.

2.2.2 Routing Architecture

Another classification is based on the vision of the routing protocols for the network and the role that they assign to the different mobile nodes in order to construct the routing topology. Based on this philosophy, routing protocols can be seen as either **hierarchical** routing protocols or **flat** routing protocols. In a hierarchical protocol, certain nodes are elected to be responsible for particular functions, leading to a multiple levels topology. This topology views the network as a division of clusters, with a cluster head node selected for each cluster to be responsible for the transmission between any two nodes at different clusters. On the other hand, flat routing protocols consider that all the nodes are equal and have the same level. The decision of a node to route a packet to another node depends on its position in the network, and may change within time according to the link connectivity constraints.

The use of hierarchical routing has several advantages, like the reduction in the size of routing tables, better scalability, and less energy consumption. However, the cluster heads should be the major elements in routing invoking certain type of centralization that does not always outfit in an ad hoc distributed environment, as well it limits to some extent the fault tolerance behavior. On the other hand, the flat routing approach provides more possible routes, with no critical nodes constraint. But it may causes congestion due to the larger number of control messages that are being transmitted among all nodes.

2.2.3 Communication Reliability

We can find other routing protocols classification according to some localization characteristics; these protocols try to improve the routing performance through effectively using approximate locations for mobile nodes. Two categories of protocols exist under this classification: **PLI-based** protocols that propose to take advantage of the Physical Location Information (PLI) for routing, and **ALI-based** protocols that use an Approximate Location Information (ALI) for each mobile node based on an existing geographical reference point. PLI-based protocols simplify the routing process by giving the physical locations for mobile nodes; such location information can be obtained by using the global positioning system (GPS). Actually, this approach invokes an increase in the cost of equipments and battery consumption. However, it remains useful in outdoor applications, such as emergency disaster relief after a hurricane or an earthquake. While ALI-based routing protocols regard the network as logical subnets; each subnet has a landmark node as a reference point. This approach is more effective at group mobility cases, when nodes have a commonality of interest and are likely to move as groups. The expected advantage in this approach is that it improves scalability through reducing routing tables sizes as well as traffic overhead, and provides robustness to shifts in mobility pattern.

We also consider a fourth classification for routing protocols exploiting the **connectivity quality** between the nodes. Actually, we believe that the connectivity quality is an essential requirement in a dynamic environment like the ad hoc environment. We consider that a connectivity quality is provided if the routing topology encompasses links with appropriate lifetime under various degrees of mobility. The satisfaction of such condition or characteristic, can highly assure a robust routing topology that guarantees a qualitative transmission in terms of continuity, signal quality, less network load, and less consumed power. Routing protocols under this classification try to exploit the **stability characteristic** between the mobile nodes, as well as the **signal quality characteristic** in order to provide a qualitative communication. These types of protocols succeed to provide a routing topology with more stable paths and thus they minimize the networks flood caused by consecutive paths fails, which in turn minimizes the battery consumption. Also, these protocols find great interest in applications that require a high degree of transmission continuity as well as applications including equipments of limited power resources.

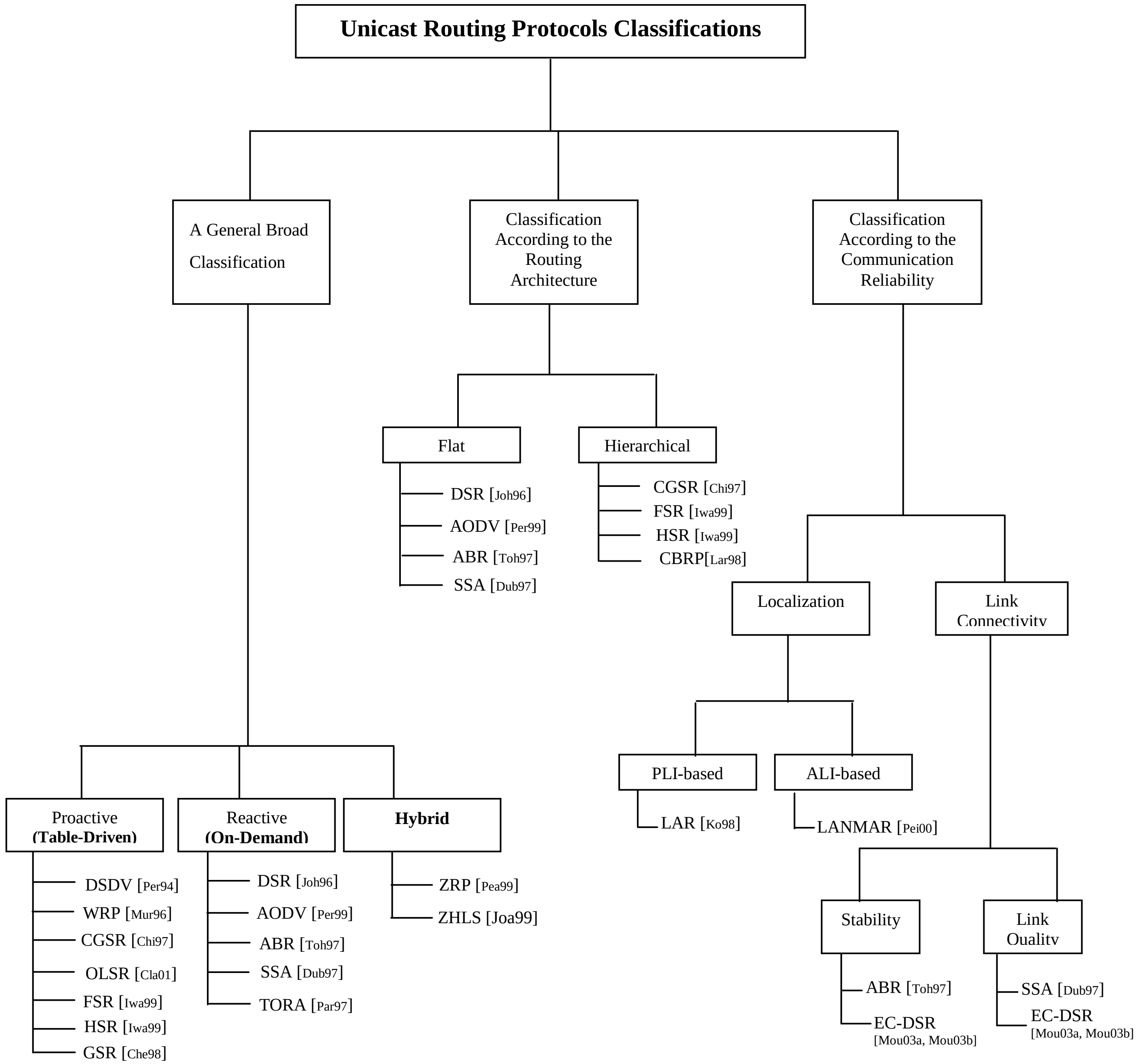


Figure 2.1 Ad hoc Routing Protocols Different Classifications

2.3 Current Ad hoc Routing Protocols

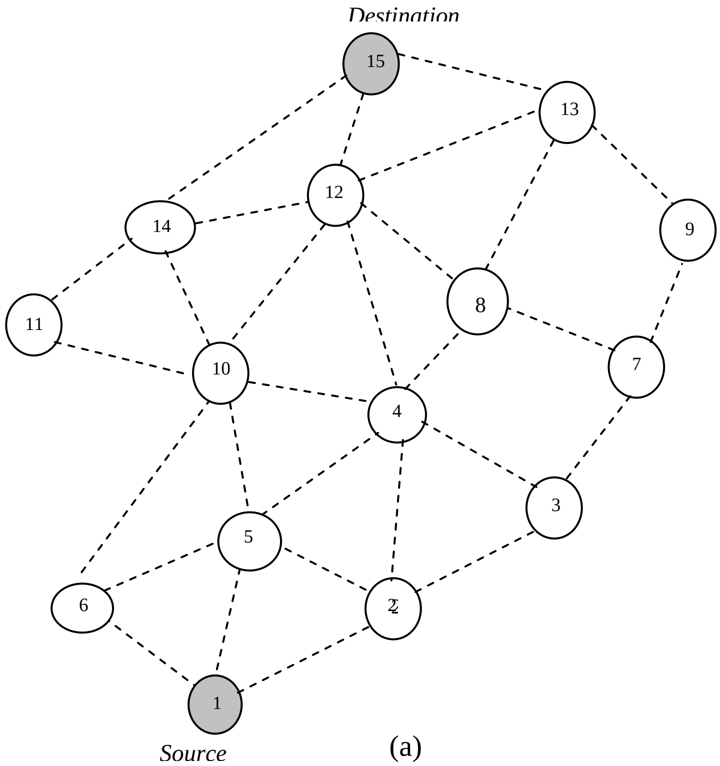
2.3.1 Destination-Sequence-Distance-Vector (DSDV) Routing Protocol

DSDV [Per94] is a hop-by-hop distance vector routing protocol. Each mobile node maintains a routing table that stores for all reachable destinations the next-hop and number of hops to reach that destination, and the sequence number assigned by the destination. The routing tables' updates are time-driven and event-driven, in which each mobile node transmits periodically its tables to its neighbors, periodically broadcasting routing updates. This transmission takes place also in topology change cases. DSDV applies two types of routing updates: full dump or incremental update. Full dump carries the full table with all available routing information and this is suitable for fast changing networks. Incremental dump carries only the updated entries since last dump, which must fit in a packet and is suitable when network is stable.

Operation: Figure 2.2, illustrates an example of the routing establishment phase in DSDV. Each node advertises a monotonically increasing sequence number for itself to all mobile nodes, at the same time it periodically transmits updates of its routing table to its current neighbors. Broken links may be detected if no broadcasts have been received for a while from a former neighbor, or the MAC layer may detect it. When a link to next hop is broken any route through that hop is immediately assigned an infinite metric and a sequence number that cannot be correctly generated by any destination node. Each node hearing this update will record this information for that destination in its routing table and propagates the information further. This continues until the destination broadcasts a new sequence number in a periodic update.

There are two approaches in which triggered updates are sent for broken nodes [Bro98]. In the first approach (DSDV-SQ), the recipient of a new sequence number for a destination should cause a triggered update. The second approach is called simply DSDV, where only the recipient of a new metric should cause a triggered update. DSDV-SQ provides much better packet delivery ratio, since broken links will be detected by the propagation of new sequence numbers, but it is much more expensive in terms of overhead. However, DSDV is much more conservative in terms of routing overhead but more data packets are dropped because link breakages are not detected as quickly as DSDV-SQ.

Properties: DSDV possesses routes availability to all destinations at all times, which involves much less delay in the route setup process. The use of sequence number distinguishes stale routes from new ones, where routes with higher sequence numbers are favorable. However, the updates due to broken links lead to a heavy control overhead during high mobility, proportional to the number of nodes in the network and therefore affecting scalability. This protocol has a destination synchronization characteristic, where a node has to wait until it receives the next update message originated by the destination in order to update its table entry for that destination.



(a)

Destination	Next hop	Distance	Sequence Number
2	2	1	22
3	2	2	26
4	5	2	32
5	5	1	134
6	6	1	144
7	2	3	162
8	5	3	170
9	2	4	186
10	6	2	142
11	6	3	176
12	5	3	190
13	5	4	198
14	6	3	214
15	5	4	256

(b)

Figure 2.2 Example of DSDV Routing Establishment Phase: (a): Network Topology, (b) Routing Table of Node 1

2.3.2 Dynamic Source Routing (DSR) Protocol

DSR [Joh96] protocol is an on-demand routing protocol, based on the concept of source routing. Each data packet follows the source route stored in its header, giving the address of each node through which the packet should be forwarded in order to reach its final destination. Mobile nodes maintain route caches containing the source routes that the nodes have learned. DSR uses no periodic routing messages, and relies on the MAC layer support for link failures detection.

Operation: DSR has two basic modes of operation, which are *route discovery* and *route maintenance*. When a node wants to send a packet to a destination, it checks its routing cache if there is an existing route to that destination. If it finds a route, then it uses it to send the packet to the destination. Otherwise it starts the route discovery process.

Route Discovery: Figure 2.3 shows the route discovery process from the source node N_1 to the destination node N_8. In Figure 2.3 (a), N_1 broadcasts a route request (*RREQ*) packet containing the source address, the destination address and a unique identification number so that each node processes the *RREQ* only once. Each intermediate node appends its address to the route record of the packet, which is formed during the *RREQ* propagation, and forwards it to its neighbors. A route reply (*RREP*) is generated when the destination node or an intermediate node with routing information about the destination is reached. At that time the *RREQ* packet is containing a route record yielding the sequence of hops taken. In Figure 2.3 (b), the destination node N_8 generates the *RREP* back to the source by placing the route record from route request packet into the route reply packet. Otherwise, if an intermediate node generates the *RREP*, then it appends its cached route to the destination to the route record in the *RREQ* packet and then generates the *RREP* packet. In the *RREP* return, if symmetric (bi-directional) links are supported, the replying node reverses the route in the route record. If symmetric links are not supported, the node checks if it has a route to the initiator, it uses it. Otherwise, it initiates its own route discovery and Piggyback the *RREP* on the new route request targeted at the initiator of the route discovery to which it is replying [Joh96]. Finally, the source caches the route carried by the *RREP* that it receives for future use.

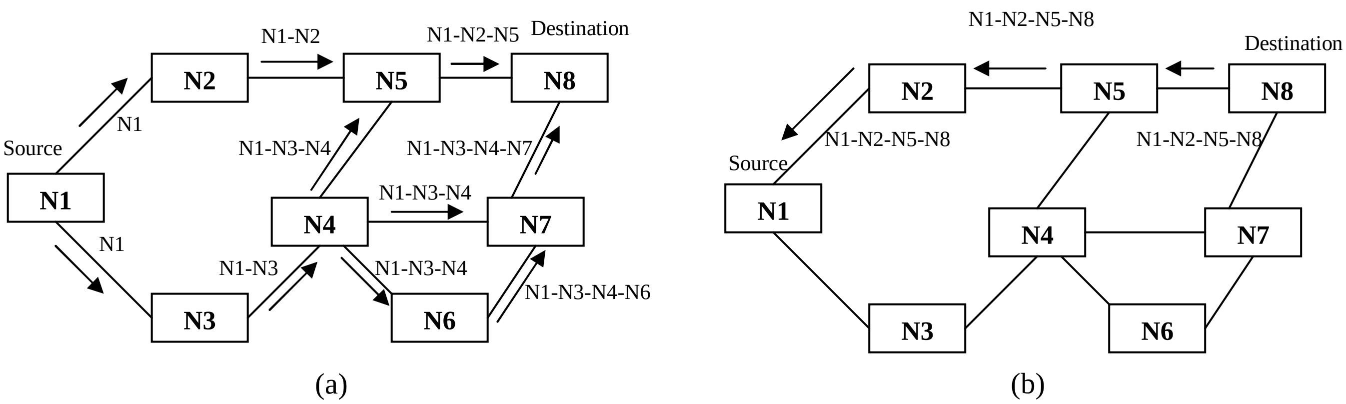


Figure 2.3 Creation of the Route Record in DSR: (a) Route record construction during route discovery, (b) Propagation of RREP

Route Maintenance: when the data link layer encounters a fatal transmitting problem, route error (*RERR*) packets are generated at a node to the original sender of the packet encountering the error. A node receiving a *RERR*, removes the hop in error from its cache and all routes containing the hop are truncated at that point. In addition, acknowledgments are used to verify the correct operation of route links. Such acknowledgments include passive acknowledgments, where a node is able to hear the next hop forwarding the packet along the route.

DSR employs some optimizations to the basic operation of the route discovery and route maintenance, which can reduce some overhead and improve the efficiency of the used routes. These optimizations take the form of promiscuous mode, non-propagating route requests, salvaging, and gratuitous route repair [Bro98, Per01].

Properties: DSR uses no periodic routing messages, i.e. no route advertisements, thereby reducing network bandwidth consumption, minimizing control overhead, conserving battery power and avoiding large routing updates throughout the ad hoc network. DSR takes a great advantage from the source routing concept, where intermediate nodes do not need to maintain up-to-date routing information, as the packets themselves contain all routing decisions [Bro98]. Moreover, loop formation is eliminated and the source learns all possible routes to the destination as well as to the intermediate nodes [Das00], however, each packet carries a considerable routing overhead due to carrying the source route, which is directly proportional to the path length. Although, DSR makes an aggressive use of caches, replying to all requests reaching a destination from a single request cycle, stale route cache information may cause inconsistency during the route construction phase. We note that the DSR route maintenance mechanism does not locally repair a broken link [Per01].

2.3.3 Zone Routing Protocol (ZRP)

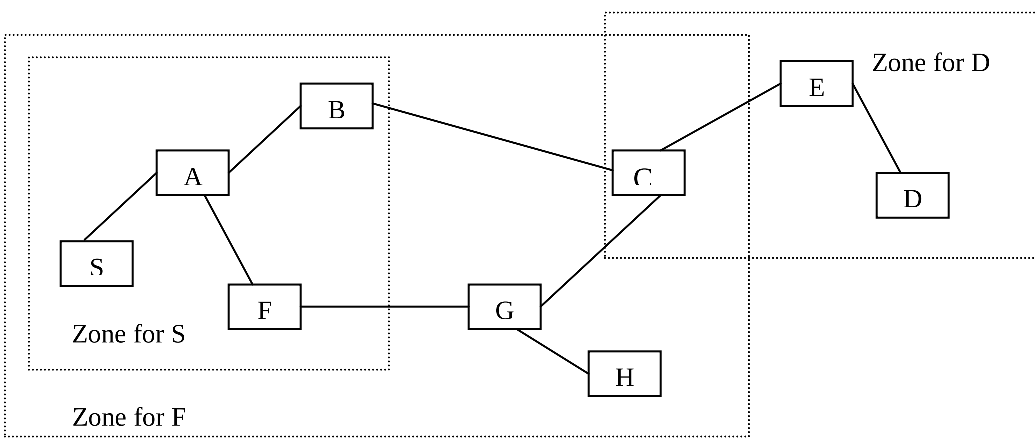


Figure 2.4 Network using ZRP

ZRP [Pea99] is an example of a hybrid reactive/proactive routing protocol. On one hand, it limits the scope of the proactive procedure only to the node's local neighborhood. On the other hand, the search throughout the network, although it is global, is performed by efficiently querying selected nodes in the network; as opposed to querying all network nodes.

ZRP divides the network into several routing zones and uses two totally detached protocols for operating inside and between these zones. The first protocol is the *Intrazone Routing Protocol (IARP)*, which operates inside the routing zones. This can include any number of proactive protocols, where different zones may operate with different IARPs. The second protocol is the *Interzone Routing Protocol (IERP)*, which is a reactive protocol used to find routes between zones. It is only useful when the destination node does not lie within the source node routing zone. A routing zone may take several definitions; the most popular one includes the nodes whose minimum distance in hops from the node in question is not greater than a parameter referred to as zone radius [Pea98]. Nodes can be defined in each zone either as border/peripheral nodes or as interior nodes. The former, are nodes having a minimum distance exactly equal to the zone radius from the node in question, while the latter are the remaining nodes. Figure 2.4, shows an example of using ZRP. Nodes *S*, *A*, *F*, *B*, *C*, *G* and *H* lie in the routing zone of *F* (the zone radius is equal to two). *B* and *F* are border nodes to the routing zone of *S*.

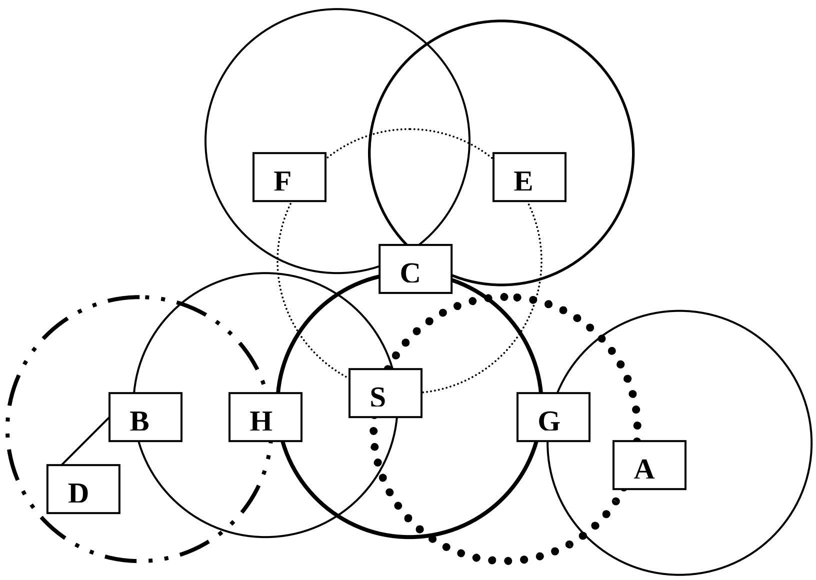


Figure 2.5 An Example of ZRP Operation

Operation: Figure 2.5, illustrates an example of ZRP operation. The source node *S* needs to send a packet to destination *D*. *S* maintains routing information to all nodes belonging to its routing zone, through locally propagating routing updates using an IARP proactive protocol. It first checks for *D* within its routing zone and discovers that it is not found. It then bordercasts queries to its peripheral nodes, *C*, *H*, and *G*, using the IERP that is responsible for discovering routes, in a reactive approach to destinations that are located outside the zone routing coverage. Nodes *C*, *H*, and *G* in turn perform the same check for *D* discovering that it does not exist in their zones and bordercast the query to their peripheral nodes. *B* the peripheral to *H* discovers *D* in its routing zone responding to the query with the forwarding path *S*-*H*-*B*-*D*.

The bordercasting is a packet delivery service that allows nodes to direct a message to its border nodes. ZRP provides this service through a component called Bordercast Resolution Protocol (BRP) [Pea98]. The intuition behind the ZRP is to perform more efficient querying by bordercasting queries to the peripheral nodes of routing zones. However, problems can arise because the routing zones can heavily overlap and a node may be a member in many routing zones, as shown in Figure 2.5. Appropriate mechanisms of query control are developed to reduce the amount of traffic, such as loop-back termination, query detection, early termination, and selective bordercasting [Pea99, Pea98].

Properties: ZRP takes advantages from both proactive and reactive approaches, reducing the control overhead compared to the route request flooding mechanism in on-demand protocols and the periodic flooding in table-driven approaches. However, in the absence of a query control mechanism, it tends to produce higher control overhead. The fact that no proactive protocol is specified in the routing zones and the nodes support to different protocols is not a good idea when dealing with thin clients. Furthermore, the decision on the zone radius has a significant impact on the protocol's performance although it may provide an adaptive behavior.

Table 2.1 summarizes the DSDV, DSR, and ZRP protocols which represent typical examples of proactive, reactive and hybrid routing schemes.

Table 2.1 Comparison Between DSDV, DSR, and ZRP

Parameters	DSDV	DSR	ZRP
Loop-Free	YES	YES	YES
Multiple Routes	No	YES	No
Distributed	YES	YES	YES
Reactive	No	YES	Partially
Uni-directional Link Support	No	YES	No
QoS Support	No	No	No
Multicast	No	No	No
Security	No	No	No
Power Conservation	No	No	No
Periodic Broadcast	YES	No	YES
Reliable or Sequenced Data Required	No	No	No

2.3.4 Location Aided Routing (LAR)

LAR [Ko98] utilizes the location information to improve the routing efficiency through reducing the control overhead. It assumes the availability of the global positioning system (GPS) to obtain the geographical position information necessary for routing, where each mobile node is provided with its physical location. The search for a new route is limited, to a smaller request zone, where the mobile node is assumed to be moving in a two dimensional plane as shown in Figure 2.6: the *expected zone* which is the region in which the destination node is expected to be present, and the *request zone* which is the geographical region within which the control packets can propagate. Additional area may be included in the request zone, if the first attempt for obtaining a path to a destination fails.

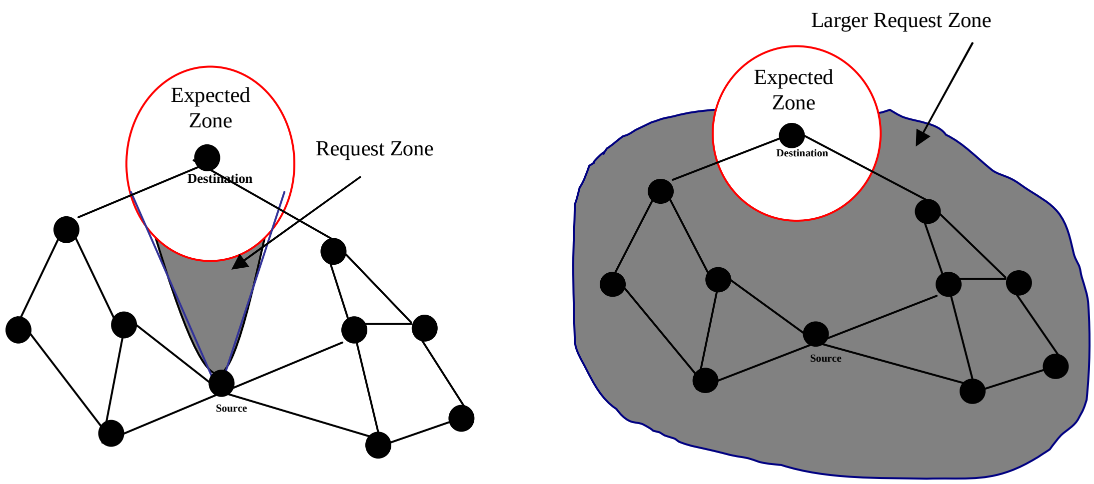


Figure 2.6 Expected and Request Zone

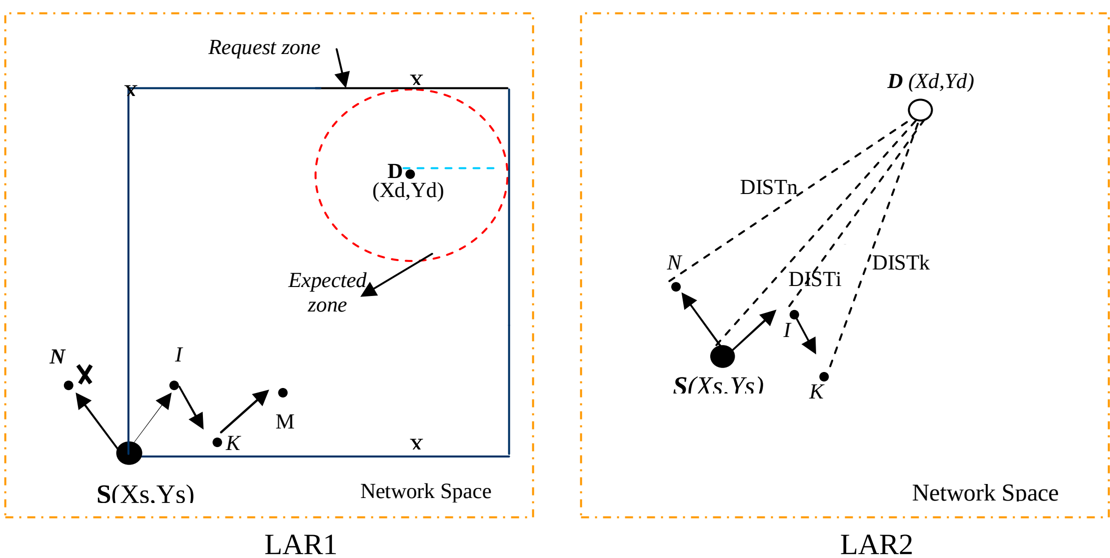


Figure 2.7 Comparison of LAR1 and LAR2

LAR uses a restricted control packets flooding on a small geographical region. Nodes decide to forward or discard the control packets according to two schemes *LAR1* and *LAR2*. Figure 2.7, illustrates an example of these two schemes in transmitting the request packet from the source *S* in a discovery for the destination *D*. In LAR1, the source node explicitly verifies the request zone in its request packet, where intermediate nodes forward the packet only if they are in the request zone. In LAR2, the source includes in the request packet the distance between itself and the destination node together with the coordinates (X, Y) of the destination. An intermediate node receiving the request packet, computes its distance to the destination, if it is less than the distance from the source then it forwards the packet otherwise it discards the packet. In Figure 2.7, the intermediate node *N* forwards the request packet in LAR2 scheme as its distance toward the destination is less than that of *S*, while it discards the request packet in LAR1 scheme as it is outside the request zone.

LAR efficient use of geographical position information reduces the control overhead and increases the bandwidth utilization. However, the application of this protocol heavily depends on the availability of GPS infrastructure or similar sources of location information.

2.4 Current MANET Routing Protocols

Realizing the necessity of standards in the emerging ad hoc network area, the mobile ad hoc networks (MANETs) working group [Iet04] was formed within the Internet Engineering Task Force (IETF). The main goal of this working group is to standardize the protocols and routing functionality in order to support the self-organizing ad hoc wireless networks. This working group normalizes the specifications of a number of core routing protocols to experimental RFC status (e.g. DSR, AODV, OLSR, and TBRPF [Bel99]). These protocols provide a basic set of routing capabilities covering reactive and proactive routing schemes, as well as a number of reliable implementations tested on real ad hoc networks platforms.

AODV [Per99] is a reactive protocol that comes as an improvement on DSDV, where it establishes routes on-demand minimizing the number of required broadcasts. Freshest routes are used, thanks to introducing destination sequence numbers. Compared to DSR, this protocol employs periodic beaconing leading to unnecessary bandwidth consumption. However, it applies a more effective error recovery scheme in case of link failures.

OLSR [Cla01] is a proactive protocol, which comes as an optimization of the pure link state algorithm. The key concept in OLSR is the use of multi-points relays (*MPRs*), which are selected nodes that forward broadcast messages during the flooding process. This protocol is suitable for large and dense mobile networks compared to other table-driven protocols, as it reduces the size of control messages and provides optimal routes in terms of number of hops (routes containing only *MPRs*).

2.5 Mobility Models

Mobility management faces many challenges in ad hoc networks. We believe that the routing enhancement can be achieved through seeking a mean to model and exploit knowledge of various mobility profiles for the nodes. Actually, the ad hoc networks routing performance is strongly influenced by the nature of the nodes' mobility pattern.

Most of the simulation work in ad hoc networks evaluates the routing performance using only the Random Waypoint (RWP) [Cam02] model. This model provides limited simulation scenarios, where all mobile nodes move randomly in the area, which is not realistic in emulating mobile nodes movements in the real world. In fact, varying mobility characteristics are expected to have a significant impact on the routing protocols performance.

In this section, we give a brief description of the existing mobility models in ad hoc networks. Then we present our proposed Robot-based Mobility Patterns (*RMP*) in Section 2.6. These patterns are tested in an ad hoc network running the DSR unicast protocol. Our obtained results investigate its impact on the network connectivity, with CBR and video traffic types.

Throughout the rest of our work, we focus on group mobility due to its suitability to large number of ad hoc applications that invoke movement in groups. More precisely, we consider two group mobility models, which are the reference point group mobility (RPGM) [Hon99] and pursue [Cam02] models. In Chapter 4, we carryout our unicast simulation performance evaluations using these two models. We compare their impact on the routing performance with that of the Random Waypoint (RWP) model, which is commonly used in ad hoc routing performance evaluation. In Chapter 5, we use the RPGM model in evaluating our multicast routing performance. We compare its impact with that of RWP model, showing the suitability of RPGM in emulating multicast nodes movements.

2.5.1 Entity and Group Mobility Models

Since MANETs are often analyzed through simulations, their performance results depend slightly on the simulation network parameters. Thus, the evaluation of an ad hoc routing protocol depending on the selected mobility model should be carefully chosen to illustrate the realistic movements of users.

Entity mobility models represent mobile nodes whose movements are independent of each other. On the other hand, group mobility models represent mobile nodes whose movements are dependent on each other and they tend to be more realistic in applications involving group communication.

2.5.1.1 Entity Mobility Models

Random Walk Model: [Zon97] developed by Zonoozi and Dassanayake, to mimic the unpredictable movement. A mobile node in this model moves from its current location to a new location by randomly choosing a direction and speed in which to travel. The new speed and direction are both chosen from pre-defined ranges, [$speed_{min}$, $speed_{max}$] and [0, 2π] respectively. A mobile node reaching the simulation boundary, bounces with an angle determined by the incoming direction then continues along the new path.

Random Waypoint (RWP) Model: [Bet02] defined by Johnson and Maltz. All nodes are uniformly distributed around the simulation space and movement of nodes has pause and motion periods. A mobile node begins by staying in a one location for a fixed pause time. After that, it selects a random destination and moves towards that destination with a speed uniformly distributed over [0, $speed_{max}$]. Upon reaching the destination, the node pauses, and then repeats the process along the simulation time. This model is memoryless where current locations are independent of precedent ones. Unfortunately, the simplicity of this model is not always adapted to describe complex mobility behavior of users.

Random Direction Model: [Roy01] developed by Royer el al. It comes as a modification on RWP model. In RWP, the probability of a mobile node to choose a new destination located at the centre of the simulation area or travelling through the centre is high. This model tries to alleviate this behavior, providing a semi-constant number of neighbors throughout the simulation. Mobile nodes choose a random direction in which to travel as Random Walk Mobility model, where they travel to the border of the simulation in that direction. Once the boundary is reached, the mobile node pauses for specified time, chooses another angular direction between (0 and 180) then continues the process.

Brownian Motion Model: [Tur01] it is a totally random motion pattern. The direction of movement is a continuous random variable between 0 and 2π and the velocity is also random at any given time. Each mobile node moves into a certain amount of space after a random period, where the movement is completely isolated.

Manhattan Grid Model: [ETS98] this model is proposed to model a city section with streets crossing each other perpendicularly. Each mobile node starts from a random point on a certain street, then choosing a random destination and moves toward this destination within a predefined speed range. Upon reaching the destination the node pauses for a certain time before repeating the process. It is assumed that nodes move only vertically or horizontally on the maps.

Random Gauss-Markov Model: [Lia99] it is an incremental model. Each mobile node is assigned initially a current speed and direction. After each time increment, the speed and direction of mobile nodes randomly diverge from the previous speed and direction.

2.5.1.2 Group Mobility Models

Pursue Model (PM): [Cam02] defined by Sanchez. It attempts to represent mobile nodes tracking a specific target called ‘leader’. This kind of behavior is found in multiple robotics activities (e.g: people or equipment tracking). A particular node in each group acts as the ‘leader’, and it moves according to one of the entity mobility models usually the RWP model. The remaining nodes in the group move towards the leader. These pursuing nodes choose a uniform random speed in the range [$speed_{min}$, $speed_{max}$]. Nodes velocity is not changed on the fly. The next position of each mobile node is calculated as a function of the current location, a random vector and an acceleration function, using a single update equation (see Equation 2.1).

$$New\_Position = Old\_Position + acceleration\,(target - Old\_Position) + Random\_Vector \quad (2.1)$$

Reference Point Group Mobility (RPGM) Model: [Hon99] defined by Hong, Gerla et al. It encompasses a random motion of a group of mobile nodes as well as a random motion of each mobile node within a given group. Each group has its own mobility behavior. There is logical “center” for each group, such that the center’s motion defines the entire group’s motion behavior (including location, speed, direction, and acceleration), and it follows the RWP model. Every node, within a specified group, follows this logical center. The motion of the groups is explicitly defined by giving a motion path for the center, which is viewed as a sequence of checkpoints. Individual mobile nodes belonging to a group randomly move about their own pre-defined reference points, whose movements depend on the group movement.

Nomadic Community Mobility: [San99] developed by Sanchez. It represents groups of mobile nodes that collectively move from one point to another. Within each community of group of mobile nodes, individual nodes maintain their own personal space where they move in random ways. An example of this model is a group of tourists visiting a museum, the whole group moves together to the museum and then each tourist may roam individually around a particular location.

Column Mobility Model: this model is useful for scanning or searching purposes, it represents a set of mobile nodes moving around a given line or column [San01]. Motion is in a forward direction. Mobile nodes are initially distributed more or less like a row, such that the whole row moves in some direction. An example of this model is a row of soldiers moving together towards their enemy.

2.5.2 Related Work

Royer et al., have performed a related study in [Roy01], developing their *Random Direction* model. They demonstrated in this study that the *Random Direction* model causes many fewer fluctuations in the node distribution compared to the *Random Waypoint* model. It is also shown that reactive ad hoc routing protocols will have different optimal connectivity levels with the difference in the mobility pattern.

In [Tur01], the authors claim that if the movement pattern of the nodes is absolutely deterministic then the route lifetime can be exactly determined. On the other hand, a chaotic mobility pattern brings in uncertainty to the route lifetime. The authors highlighted the important role of mobility models on the route lifetime. They also showed that it highly depends on the speed and direction of movement of all the involved nodes.

A performance study is presented in [Che03] for four ad hoc routing protocols with different mobility models, focusing on their energy conservation performance. The purpose of this work is to identify the challenges that the different mobility models impose on energy conserving in ad hoc networks. The results confirm that energy consumption of ad hoc routing protocols varies significantly with the node mobility pattern. It is also noticed that when nodes move in groups, on-demand protocols perform better than proactive ones in terms of energy conserving. In a highly dynamic environment such as *Manhattan Grid*, on-demand protocols performance decreases and proactive protocols save more power.

A graph-based mobility model is introduced in [Tia02], in which the nodes do not move randomly, but always along the edges of a graph that models the given infrastructure. Initially, each mobile node starts at a random vertex where it selects randomly another vertex as a destination and moves towards it using the shortest path on the edges. Routing protocols were tested using this model together with the random walk model, where great difference in performance is realized between the two models. Similarly, the graph-based model shows very different impact with different routing strategies.

The development and use of mobility models for low speed hosts is considered in [Elm01]. A mobile node moves along a number of geographical locations spending some time in each location before moving to another location. The authors consider the environments where the users exhibit a probabilistically predictable spatial behavior. Using this model, an efficient exact solution is presented for a special case of estimating the probability that all hops of a given route coexist simultaneously, and a heuristic solution for selecting a high probable route that achieves a certain load-balancing criteria.

2.5.3 Emerging Tools/Frameworks

Indeed, the *Random Waypoint* model, which is used in most of the ad hoc simulation studies under (*ns*-2, glomosim, Qualnet, and opnet), does not consider some significant mobility characteristics. Firstly, *spatial dependency* is not considered where each mobile node moves independently of the others ignoring the neighborhood influence on the nodes' movements. Also, *temporal dependency* is not considered, such that mobile nodes velocities are independent. However, in reality, the mobile node velocity should not change abruptly due to the physical constraints of the mobile entity itself. Furthermore, the *Random Waypoint* model does not include the *geographic restrictions*, where the movement of a mobile node may be restricted by a street map or city boundaries. To thoroughly study the effect of mobility on MANET protocols performance, some tools and frameworks have emerged developing a set of mobility models in order to provide a richer environment for routing protocols evaluation. We present three major tools:

IMPORTANT: [Bai03a, Bai03b] a framework comes to analyze and evaluate the impact of different mobility models on the performance of MANET routing protocols. A set of mobility models is introduced in this framework including *Random Waypoint*, *RPGM*, *Manhattan*, and *Freeway* models.

ANEJOS: [San01] an ad hoc network Java simulator. It considers some relevant aspects to ad hoc networks as the mobility patterns and the traffic generation patterns. This simulator introduces *Brownian Motion* model, Exponential *Correlated Random* model, *Column*, *Pursue*, and *Nomadic Community* models.

Bonn-Motion Tool: [ics] a mobility scenario generator and analysis tool. It supports *Manhattan Grid*, *Reference Point Group Mobility*, *Gauss Markov*, and *Random Waypoint* models.

2.6 The Robot-based Mobility Patterns (RMP)

In this section, we aim to emulate the behavior of people in a conference, making use of an ad hoc network to achieve some useful services. This work was carried out as part of "Ambience ITEA" project, and aims to model meetings and conferences environment that involve ad hoc networks. In this context, we developed a set of mobility patterns to model a variety of movements for conference participants. This model is useful in applications that include a Host Management System *(HMS)* where each participant is provided with some useful services like automatic registration, guidance in finding a meeting room, connection to the Internet, various types of data transmission during a whole conference or during a meeting. Our model, named *Robot-based Mobility Patterns* (*RMP*), is based on the existence of a collection of robot nodes trying to satisfy each participant (mobile node) with the required services. The robots are responsible for all the data transmission between the Conference Participants (*CPs*) and an *HMS* server, where they communicate together to offer seamless communication. We developed six different mobility patterns to cover all the possible behaviors for mobile nodes in such applications. The mobility patterns are described in the following subsections, assuming that each *CP* is equipped with a Personal Digital Assistant (*PDA*) or a laptop computer to form an effective ad hoc node. While each *HMS* stores necessary registration information, all necessary information for the meetings, different databases, and is capable of connecting to the Internet in its stationary and mobile states.

Mobility Pattern 1: all the nodes are in a stationary state, modeling the initiation phase. It emulates the case of a *CP* node arrival, starting to register at a pre-defined position in the reception area. The *robot* nodes are scattered in stationary positions covering the area, and offering the communication between the *CP* node and the *HMS* node which is a stationary server in this case.

Mobility Pattern 2: the *CP* and the *HMS* nodes are stationary, while the *robot* nodes move in separated groups. We assume that individual *robot* nodes move randomly within each group. This pattern emulates "find a meeting" case, in which the *CP* node is stationary in a random position searching for the meeting room after finishing the registration. The *robot* nodes then provide the *CP* node with the required service; through collaborating to consult the *HMS* node that is a stationary server in this case.

Mobility Pattern 3: the *CP* and the *HMS* nodes are moving in all the space, while the *robot* nodes are stationary then move in separated groups, assuming the same individual random movement in each group as pattern 2. This pattern emulates "coffee breaks" case. Where *CP* nodes are liable to spread in the whole conference area, and the robot nodes are responsible for tracking them in order to provide them with the required services. An example of the expected service in this situation is the Internet connections. Firstly, the *robots* are stationary to trace the *CP* nodes movements' direction; then they split in several moving groups serving each occupied area. The *HMS* node in this case is a mobile server, moving around the whole area.

Mobility Pattern 4: *CP* and the *HMS* nodes are stationary, while *robot* nodes are scattered in a way that each node rotates around a reference point close to it. This pattern emulates "during a meeting" case; in which the *robot* nodes are waiting to provide the *CP* nodes with any service. Thus they are in a continuous monitoring state. The *HMS* node is a stationary server in this case.

Mobility Pattern 5: *CP* and the *HMS* nodes are stationary, while *robot* nodes are moving randomly and with varying velocities. This pattern emulates "data transmission during a meeting" case, in which the *robot* nodes try to provide the required communication between the *CP* nodes or between a *CP* node and the *HMS*. The *HMS* node is a stationary server in this case.

Mobility Pattern 6: *CP* and the *HMS* nodes move randomly, while *robot* nodes move with pre-defined positions independent of *CP* and *HMS* nodes movement. This pattern emulates "end of meeting" case in which the nodes movement is somewhat unpredicted, comprising more randomness. The *CP* nodes divide for leaving, the *HMS* node moves randomly aiming to surround the whole area. The *robot* nodes scatter trying to cover the whole building.

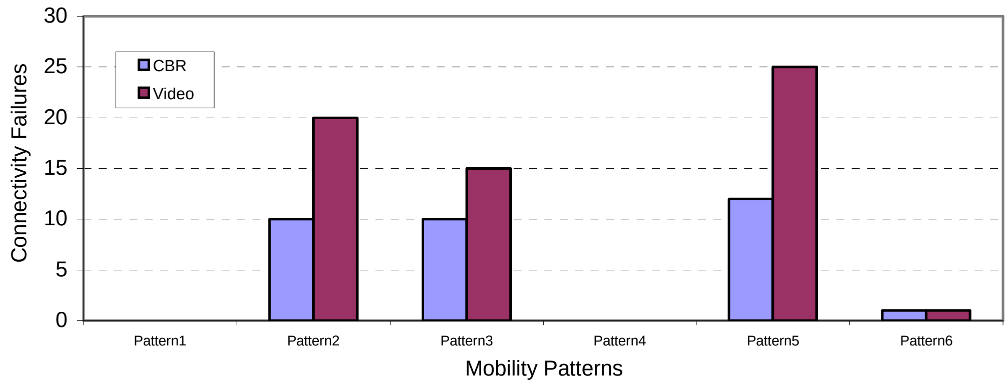


Figure 2.8 Number of Connectivity Failures

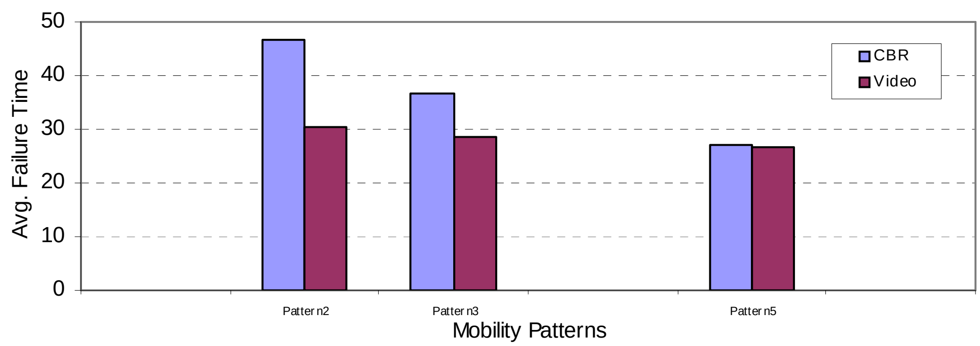


Figure 2.9 Average Time Between Consecutive Connectivity Failures

We implemented the *RMP* mobility model under Network Simulator (*ns*-2), a discrete event simulator developed at University of California, Berkeley and targeted at network research [Fall98]. To test the behavior of ad hoc routing under the six proposed mobility patterns, we configured a small ad hoc network running the DSR routing protocol with the *RMP* different patterns. Our network configuration is composed of 7 nodes including 5 *robot* nodes, a *CP* node, and the *HMS* node moving in a 500 x 500 square area. For reliable communication, we consider that each *robot* node has a sufficiently large radio coverage range. We tested the routing efficiency with the six mobility patterns using two different types of traffic: *CBR traffic* (packet size = 512 bytes, packets transmission rate = 4 packets/second, and maximum number of packets = 3000) and a *video traffic* (VBR, H.263 encoding). Because the *ns*-2 does not support video traffic generation, we created an application *TrafficTrace* object for the video traffic. This object is associated with a trace file containing video trace data obtained from a movie during 600 seconds, which is publicly available [Ari] for the test of video transmission performance, especially for wireless networks [fit01]. The video trace data are fragmented at a frame rate of 25 frames/second, and encoded into a H. 263 bit stream without setting a target bit rate (i.e. variable bit rate "VBR").

During our evaluation and analysis, we focused on studying the impact of mobility patterns on the communication reliability. By communication reliability, we mean the continuous connectivity between the *robots*, as well as the continuous connectivity between each *CP* node and at least one *robot*, and the *HMS* node and at least one *robot*.

To achieve a reasonable evaluation, we measured the number of connectivity failures and the average time between each consecutive connectivity failures. Figure 2.8 and 2.9 respectively illustrate our obtained results for these metrics. We analyzed the six different mobility patterns during 600 seconds of simulation time.

We chose the Dynamic Source Routing (DSR) protocol [Joh96] to study the effect of these different mobility patterns on the protocol's performance. In Figure 2.8, DSR provides the most reliable connectivity with mobility patterns 1 and 4, where continuous connectivity always exists for the two traffic types. This is followed by mobility pattern 6, in which DSR provides an almost continuous connectivity. Since mobility pattern 1 is a totally stationary pattern, and then the protocol shows a perfect behavior in such environment allowing a full service provision. A similar behavior takes place with mobility pattern 4, due to the localization of all nodes in the meeting room with the *CP* and *HMS* completely stationary while the *robots* are monitoring them in a rotational way. This pattern provides localized *robot* coverage and hence offers full connectivity as shown. Mobility pattern 6 resembles the conference termination where the connectivity is almost continuous for the two traffic types. Actually, there is no stationary behavior in this scenario, thus we suggest that the connectivity continuity is a function of the requested services. In other words, at the end of the conference the service that might be requested by the *CPs* is minimized, and there exists a very high chance for its satisfaction through an available current connectivity. In the other mobility patterns, the video traffic has a lesser communication reliability compared to CBR, where the number of connectivity failure is noticeably more. This returns to the stringent bandwidth requirement for the video traffic, which is very hard to maintain in ad hoc network. DSR exhibits nearly the same connectivity behavior with CBR traffic under mobility patterns 2 and 3. Thus the stationary *CP* and *HMS* state in pattern 2 does not provide better connectivity compared to pattern 3 that comprises more randomness. Furthermore, it causes a negative connectivity impact with the video traffic, showing the unsuitability of group mobility (*robots*) in video traffic cases. The lowest connectivity is illustrated with mobility pattern 5, where this pattern has a stronger negative impact with video traffic and a little negative impact with CBR traffic compared to patterns 2 and 3. In this case, the actual transmitted video data is much larger, "data transmission during a meeting", requiring more routes lifetime that could not always exist with the *robots* random movement.

To summarize our above observations and analysis, we conclude that DSR shows a difference in connectivity discontinuity of almost 30% from mobility patterns (2 and 3) to mobility pattern 5 with CBR traffic. Similar performance behavior were obtained with video traffic, where DSR exhibits a difference in connectivity discontinuity of almost 25% from mobility pattern 5 to mobility pattern 2, and a difference of almost 66% from mobility pattern 5 to mobility pattern 3.

Figure 2.9, demonstrates the average time between connectivity failures for mobility patterns 2, 3, and 5. We generally notice that DSR is more robust with CBR traffic compared to video traffic, especially with mobility patterns 2 and 3. Pattern 5 has the same impact on DSR for the two traffic cases. Also, DSR achieves the worst connectivity robustness with mobility pattern 5 in the CBR and video traffic cases.

These results show that the behavior of a routing protocol is generally dependent on the used mobility model, and suggest that care should be taken in choosing the mobility model when studying different protocols.

2.7 Discussion and Conclusion

Throughout our study, we noticed that the field of ad hoc mobile networks is rapidly growing and changing and there are many routing challenges that need to be met. The lack of standards in this area of study leads to several works and propositions; however, the validation of the routing propositions is being mainly conducted through simulation results.

In this chapter, we introduced the major challenges in the design of routing protocols in ad hoc network, illustrating the limitations of static networks routing protocols in an ad hoc environment. We noticed that the major challenges to be addressed in any routing protocol design are the nodes' mobility, dynamic topology, limited battery-power, and limited bandwidth. As well, we provided different classifications for routing protocols according to the routing approach, routing architecture, and communication reliability. The most common classification considered for almost all protocols, divides the protocols according to the used routing approach into: proactive (on-demand), reactive (table-driven), or a hybrid protocols. Table 2.2 summarizes some basic variations between the on-demand and the table-driven approaches.

Since MANETs are not widely deployed, most of the research in these networks is simulation based. The Random Waypoint (RWP) is the most commonly used mobility model in these simulations, although this model is not always sufficient to capture some important mobility characteristics in MANET scenarios. Consequently, there is a need for considering the impact of the different mobility models in the evaluation of the routing performance.

Table 2.2 General Comparison of On-demand and Table-driven Routing Protocols

Parameters	On-demand	Table-driven
Routing information availability	Available when needed	Always available
Routing philosophy	Flat	Mostly flat
Periodic route updates	Not required	Required
Coping with mobility	Using sometimes localized route discovery	Informing other nodes to achieve a consistency table
Signaling traffic generated	Grows with increasing mobility of active routes	Greater than that of on-demand routing
QoS support	Few can support QoS but most support Shortest Path	Mainly Shortest path

We also introduced the mobility models impact on the performance of ad hoc routing protocols, and we proposed the *RMP* model that reflects the mobile nodes movement behaviors in a conference like environment. In this model, the nodes do not move totally at random but rather under the constraints of six different mobility patterns. Each mobility pattern emulates a certain case probable to occur in such environment. We implemented this model under *ns*-2, and we use the DSR protocol as an illustrative example in evaluating the effect of our six proposed mobility patterns on ad hoc routing performance.

Our obtained results are consistent with the other works that study the routing behavior changes obtained with the different mobility models used. However, we attempted to analyze the reason for this performance difference considering the constraints of the *RMP* application environment. It has also been observed that the video traffic performs poor for the same scenarios applied with CBR. Acceptable performance can only be obtained when the traffic size is expected to be lesser.

In this thesis we further study mobility patterns impact on the routing performance. More specifically, in Chapter 4 and Chapter 5 we investigate the impact of mobility models on our proposed unicast and multicast routing protocols.

In the next chapter, we conduct a state of the art on multicast routing in ad hoc networks, stating the challenges and constraints in this area.

CHAPTER 3 MULTICAST ROUTING IN AD HOC NETWORKS

In a typical ad hoc environment, network hosts are frequently liable to work in groups to carry out a given task. Hence, multicast plays an important role in point-to-multipoint or multipoint-to-multipoint communications. The primary nature of the communication required in a military environment enforces a reliable and secure multicast routing. For example, the leader of a group of soldiers may want to give an order to all the soldiers or to a set of selected personnel involved in the operation. The collaborative and distributed computing, like a group of researchers who want to share their research findings or presentation materials during a conference, requires the formation of an ad hoc network with the necessary support for reliable multicasting. Further applications include emergency search-and-rescue operations, requiring communication between a set of participants. We recall that it is always advantageous to use multicast rather than unicast in an ad hoc environment, where bandwidth comes as a premium.

In this chapter, we give a general overview on multicast, stating its challenge in an ad hoc network environment and discussing the limitations of wired networks multicast routing protocols. We then present some newly proposed multicast protocols in ad hoc networks, illustrating their advantages and limitations. Finally, we conclude this chapter and highlight our motivation in proposing a new multicast ad hoc routing protocol.

3.1 A General Overview on Multicast

Multicast is used as support to group communication, where a data packet can be delivered to several destinations by a single transmission. This does not involve all machines connected to a network, but only a defined subset of these machines, that is the multicast group.

Multicast, Unicast, Broadcast, and Anycast: Figure 3.1 demonstrates the difference between unicast, broadcast, multicast, and anycast. Multicast transmission includes one emitter to many receivers, or many emitters to many receivers. In a multicast session any participant can decide whether and when it wishes to join and leave the session. Traditional transmission techniques, unicast or point-to-point communication has a source and a destination, establishing point-to-point sessions between each two participants. Connection establishment, flow control and error recovery can be driven from one end which is the active or sender end [Dio97]. On the other hand, broadcast provides diffusion from the source node to all other nodes in the network, thus consuming more bandwidth. Anycast is inspired from unicast, multicast and broadcast. It does not include diffusion but transmission to only one member of a group of receivers. This transmission occurs to any member according to the nearest call [Rou99].

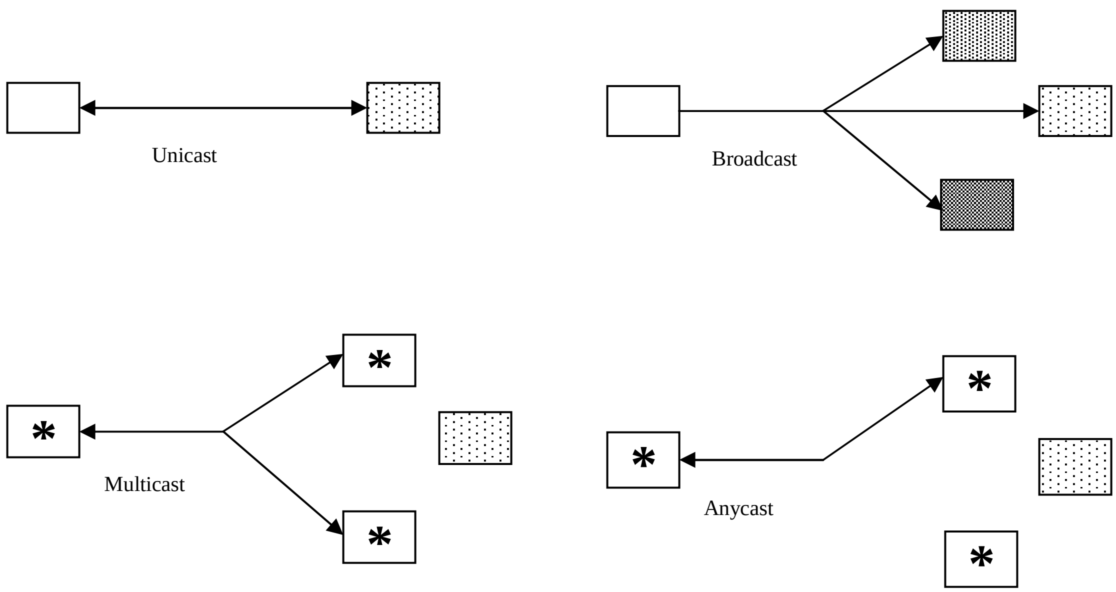
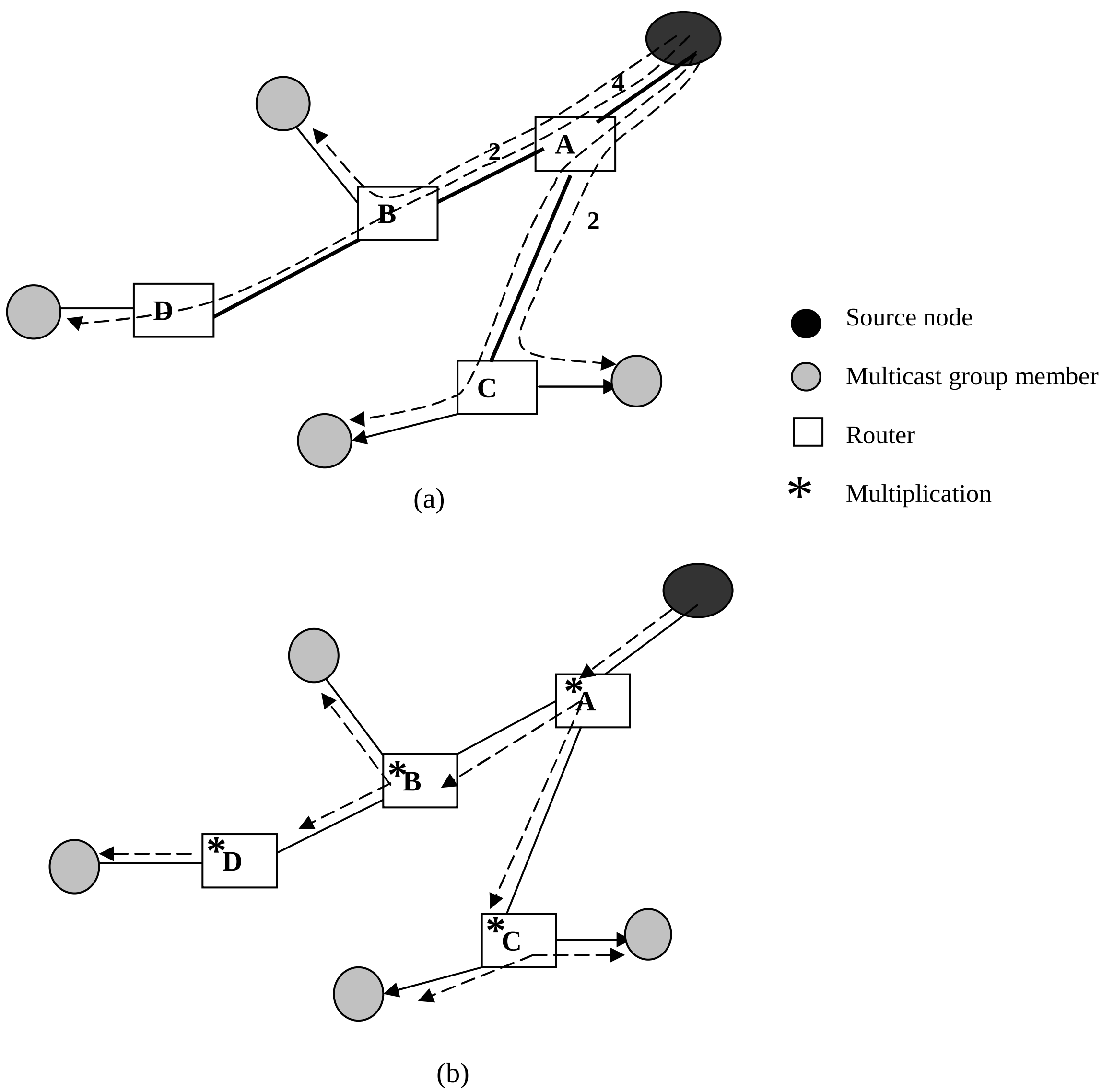


Figure 3.1 Unicast, Broadcast, Multicast, and Anycast

Benefits of Multicast: multicast is introduced for group communication to reduce communication cost. It provides efficient saving in bandwidth and network resources, since data can be transmitted to all receivers using a single transmission [Ned00]. On the other hand, in unicast technique, the source transmits the same information more than once to several destinations, the message is sent only once and then it is copied and transmitted to the different members of the multicast group. Figure 3.2 illustrates this interest in multicast. We notice the redundancy in data packet transmission, when using the unicast technique in Figure 3.2(a), over the links (*Source*-*A*), (*A*-*B*), and (*A*-*C*). When applying the multicast technique in Figure 3.2(b), no redundancy takes place during the transmission.

Requirements: multicast technique requires some technological constraints, where certain capacity is required in the network [Rou99]. First, a multicast addressing should be associated with each multicast communication and the nodes wishing to participate at the multicast session should join this address. As well, a multiplication capacity should exist at the networks nodes, where they should have the capacity for duplicating the received information. The interest of this multiplication capacity is to make economic use of bandwidth in the network.



. Figure 3.2 (a) Unicast diffusion versus (b) Multicast diffusion

Applications: multicast communication is mainly useful for multipoint or group applications, including software distribution, replicated database update, command and control systems, and distributed interactive simulation [Dio97]. Furthermore, it is of great interest for video and Internet conferences [Lee00a], as well as distributed applications including: distributed games and collaborative work such as distributed simulation and shared text processing [Ned00].

Multicast Traffic Transmission in Radio Channels: in radio channels, advantages should be taken from broadcasting capabilities of the radio interface to transmit multicast traffic to each multicast group member node. Some important functions, that are particularly important to wireless multicast, take place at the MAC layer. These functions include performing broadcast transmission/reception, detecting all neighbors, and observing link characteristics.

3.2 Multicast Routing and Technical Challenges in Ad hoc Networks

Designing multicast routing protocols in an ad hoc environment is a complex problem, as group membership can change, and network topology can highly evolve causing links failure. In addition, the limited bandwidth availability together with the limited energy resources make the design of a multicast routing protocol a challenging one. The basic simple algorithms for multicast routing in ad hoc networks are flooding-based, which are used for broadcasting multicast packets but result in low efficiency in terms of link utilization. An ideal efficient routing algorithm should design a topology covering only the group members. The major issues in designing a multicast routing protocol are as follows [Mur04, Obr98]:

Robustness: a multicast routing protocol should be robust enough to sustain the mobility of the nodes and achieve a high packet delivery ratio.

Efficiency: as ad hoc environment is characterized by a scarce bandwidth, an efficient multicast routing protocol is of great importance. Efficient routing is expected to provide a fair number of transmitted control packets in the network with respect to the number of data packets correctly received by the receivers.

Control overhead: the design of a multicast routing protocol should ensure minimized total number of control packets that are transmitted for maintaining the multicast group, and thus avoiding the bandwidth consumption waste.

Quality of service: QoS support is essential in multicast routing as, in most cases, the data transferred in a multicast session is time-sensitive.

Resource management: as ad hoc networks consist of “thin-clients” nodes, multicast routing protocol should use minimum power through reducing the number of packets transmission. Also, the minimized memory storage is important, through the use of minimum state information.

Scalability: a multicast routing protocol should be able to scale for a network with a large number of nodes.

Security: since some of the ad hoc multicast applications require a certain degree of security, as the military applications, a multicast routing protocol should provide authentication of session members, preventing non-members from gaining unauthorized information.

As we mentioned previously, designing a multicast routing protocol meets many challenges. A multicast protocol can hardly satisfy all the above requirements, but rather each protocol is designed to provide the maximum possible requirements, according to certain required specifications. Satisfying most of these requirements would provide support for reliable transmission, minimized network load, optimal routes (not necessary as a function of the number of hops), and minimized storage and resources' consumption.

A useful reference model for understanding the architecture of multicast routing protocols is presented in [Mur04]. This model considers three layers in the network protocol stack, which are concerned with multicasting in ad hoc networks. Figure 3.3, gives an architectural framework for this model.

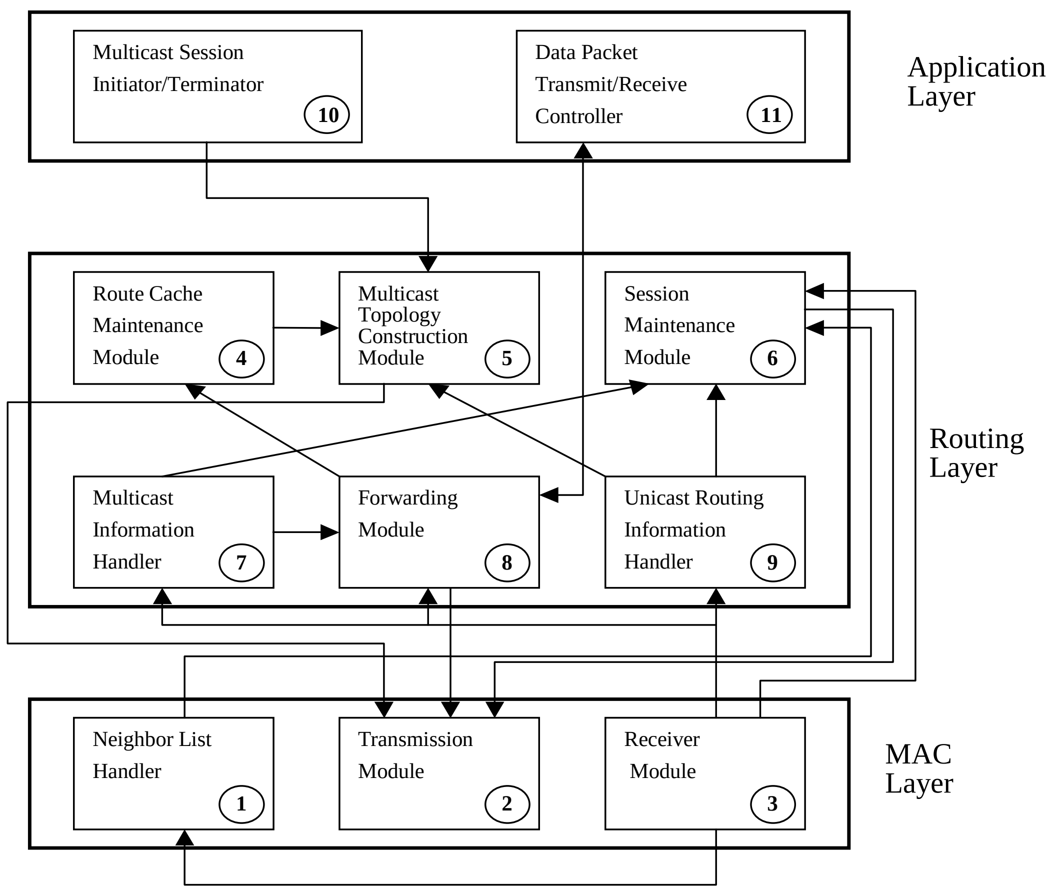


Figure 3.3 Architectural Framework of an Ad hoc Multicast Protocol

The interaction between the different modules, in Figure 3.3, is due to some actions taking place during the lifetime of the multicast session. When a node wants to join a multicast group, module 10 (application layer) makes a request to join the group to module 5 (routing layer) which can consult module 4 and module 9, then it initiates flooding of *JoinRequest* packets using module 2 (MAC layer). These *JoinRequest* packets are passed by module 3 of other nodes to their forwarding module, which updates the multicast table and propagates this message. During the reply phase, the forwarding states in the multicast tables of intermediate nodes are established. Module 11 (application layer) is responsible for handling data packets, where it passes them to module 8 (forwarding module) which makes the decision on whether to broadcast the packets after consulting module 7. This process is repeated among all the nodes belonging to the multicast topology until eventually the data packets are sent by the forwarding module of the receivers to the application layer. As noticed, route repair is handled by module 6 on being informed by module 1 of link breaks.

3.3 Conventional Multicast Protocols

Conventional wired network Internet Protocol (IP) multicast routing protocol, such as distance vector multicast routing protocol (DVMRP**)** [Wai88], multicast extension to open shortest path first (MOSPF**)** [Moy94], core based trees (CBT**)** [Bal93], and protocol independent multicast (PIM**)** [Dee96], do not perform well in ad hoc networks because of the dynamic nature of the network topology. The arbitrary nodes movements in ad hoc networks can dynamically change the topology in an unpredictable manner. Consequently, the mobility of nodes with the constraints of power source and bandwidth makes multicast routing very challenging.

The basic approach adopted for wired multicasting consists of establishing a routing tree for a group of nodes that constitutes the multicast session. Once the routing tree or a spanning tree (an acyclic connected subgraph containing all the nodes in the tree) is established, each multicast packet traverses each node and each link in the tree only once. Such a multicast structure is not appropriate for ad hoc networks because the tree could easily break due to the highly dynamic topology. In this section, we give a brief description of the tree approach used in wired multicast routing, highlighting its limitations in an ad hoc environment.

There are two popular wired network multicast schemes, namely, per-source shortest tree and shared tree. The per-source tree scheme consists of broadcasting the packet from the source to all destinations along the source tree, while avoiding loops. This takes place through employing the “Reverse Path Forwarding (RPF)”. DVMRP and PIM Dense Mode are examples of per-source tree protocols that are commonly used in the Internet. In the shared tree multicast scheme, each multicast group has a single tree rooted at a special router called Rendezvous Point (RP). Each multicast group has its own RP, and constructs its own shared tree. CBT and PIM Sparse Mode are example of shared tree protocols.

The full periodic broadcast that takes place in DVMRP introduces costly control overhead on the low bandwidth wireless channel and is not suitable for scalable networks. The shared tree works well as long as it is stable and the RP itself is not fast moving, which is not always the case in ad hoc networks. Since the entire network moves and the membership changes dynamically, the RP may not be in the center aggravating the non-optimality of the paths.

In conclusion, the tree-based multicast structure can be highly unstable in multicast ad hoc routing protocols, as it needs frequent re-configuration in such a dynamic network. Furthermore, the use of any global routing structure such as link state table like the MOSPF protocol, results in high control overhead. Providing multiple links among the nodes in an ad hoc wireless network, resulting in a mesh-shaped structure, is expected to work well in such a dynamic environment [Lee0a].

3.4 Multicast Routing Protocols in Ad hoc Networks

As discussed in the previous section, multicast protocols used for static networks do not perform well in ad hoc networks. The fact that a fragile multicast tree has to be constructed each time the connectivity changes, makes them not suitable for ad hoc networks dynamic topology. The global routing substructure in these protocols, such as link state or distance vector together with the dependence on upstream and downstream nodes, require frequent exchange of routing information causing an excessive channel and processing overhead. This is not efficient in an environment of limited bandwidth, and limited power and storage capacity.

3.4.1 Classification

To provide efficient multicast routing in ad hoc networks, a different routing approach is needed, modifying the conventional tree structure or deploying a different topology between group members like the mesh topology [Lee00a]. Since multicast routing is a complex problem, we only noticed few propositions when we began our work in this subject. In this section, we provide different multicast routing protocols classifications in ad hoc networks, and then we present some of these recently proposed protocols in Section 3.4.2.

Multicast routing protocols for ad hoc wireless networks can be broadly classified into **generic protocols** and **specific purpose protocols**. Specific purpose protocols are meant only for specific applications for which they are designed. Generic protocols are used for conventional multicast. We illustrate in Figure 3.4, different classifications for multicast routing protocols in ad hoc networks. Generic multicast protocols are classified according to the multicast topology construction approach into: **proactive approach**, and **reactive approach**. Like unicast routing, proactive approach protocols pre-compute paths periodically to all multicast destinations, storing this information in their routing tables and constructing their multicast topology. Alternatively, the reactive approach attempts to operate in an on-demand fashion, in which the operation of the protocol is driven by the presence of data packets being sent rather than by continuous or periodic background activity of the protocol. In this chapter, we rather focus on reactive multicast protocols.

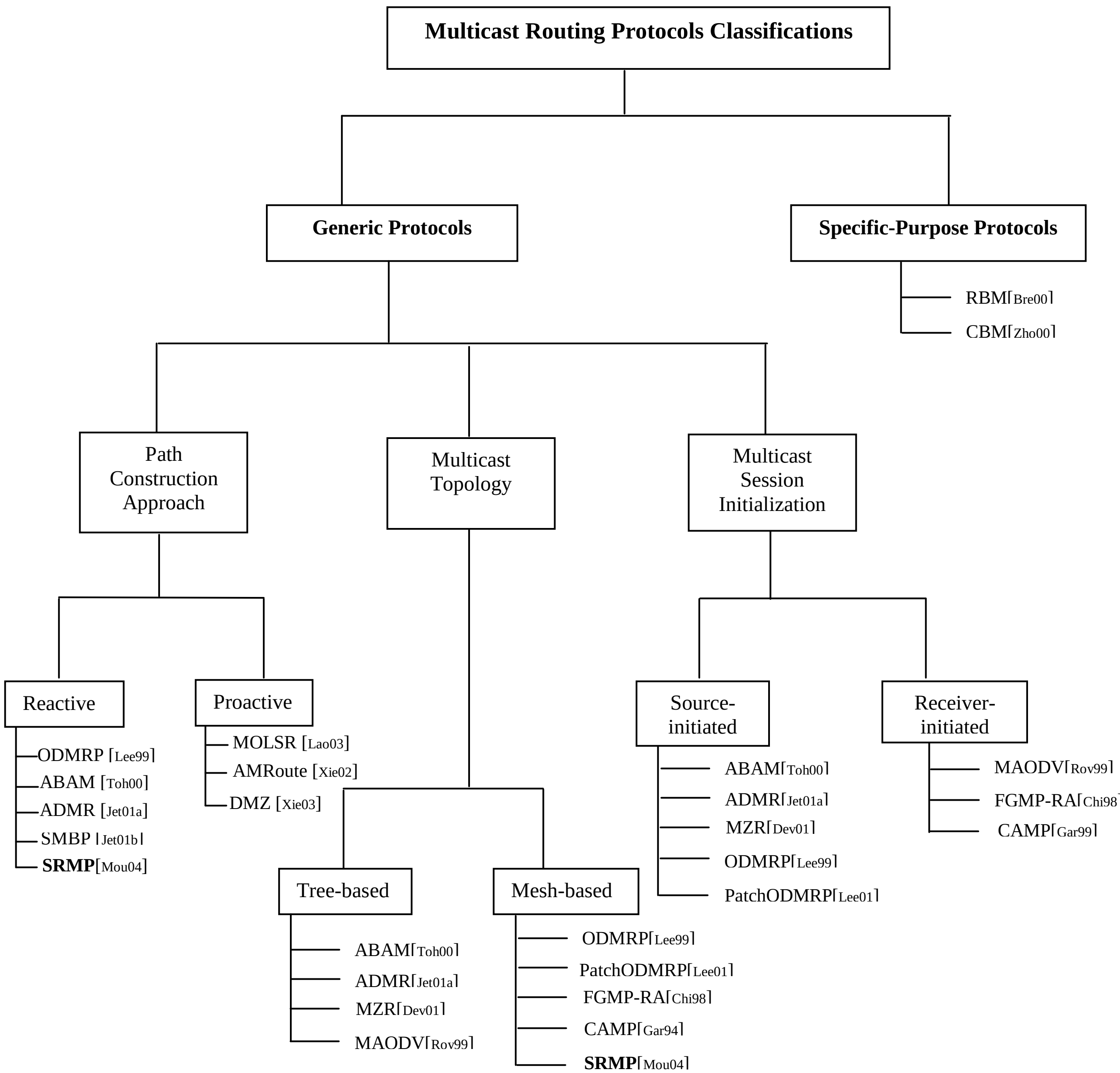


Figure 3.4 Multicast Routing Protocols Different Classifications

A second classification for generic protocols is according to the multicast topology, where protocols are classified as being either **tree-based** or **mesh-based**. In tree-based protocols, there exists only one single path between a source-receiver pair, whereas in mesh-based multicast routing protocols, more than one path may exist between a source-receiver pair. Tree-based protocols are more efficient, while mesh-based protocols are more robust in highly mobile environments due to the availability of multiple paths. A third classification for generic protocols is based on the multicast session initialization, where the multicast group formation can be initiated by the source as well as by the receivers. **Source-initiated** multicast routing protocols initiate the multicast group formation by the source, while the multicast group formation takes place by the receivers in the **receiver-initiated** multicast protocols. Actually, some protocols may not strictly fall under these two types, where they do not distinguish between source and receiver for initialization of the multicast group.

3.4.2 Multicast Routing Protocols: State of the Art

In this section, we describe some of the existing multicast routing protocols for ad hoc wireless networks. We mainly focus on on-demand multicast protocols, since we chose the reactive routing approach throughout our contributions in the thesis as they are well suited for mobile ad hoc networks [Lee0a], especially when the mobility rate is high.

3.4.2.1 Tree-based Multicast Protocols

3.4.2.1.1 Multicast Ad hoc On-Demand Distance Vector Routing (MAODV) Protocol

MAODV [Roy99a] extends AODV to offer multicast capabilities, where it builds shared multicast trees on-demand to connect multicast group members. Thus MAODV is capable of unicast, broadcast, and multicast. Combining unicast and multicast capabilities in one protocol has more than one advantage, first the protocol can be streamlined where route information obtained when searching for multicast can also increase unicast routing knowledge and vice-versa. Route discovery is formed on-demand in the form of request/reply, and information gleaned through the route request (*RREQ*) and route reply (*RREP*) is kept in the nodes routing table. Sequence numbers are used to eliminate stale routes, where routes with old sequence numbers are aged out of the system. In multicast operation, a group leader node maintains the multicast group sequence number, where it periodically updates the sequence number and broadcasts it using group hellos (*GRPHs*) messages. This group leader is typically the first node to join the group.

Operation: nodes wishing to join the group unicast a *RREQ* to the group leader if they have its address, otherwise they broadcast the *RREQ*. An illustrative example is shown in Figure 3.5(a), where the requesting node sends a *RREQ* to its neighbors *1* and *2*. Node *1* then broadcasts the *RREQ* to its neighbors *2* and *3*, and node *2* broadcasts it to its neighbors *4* and *5*. The *RREQ* propagation continues until reaching the tree members and group members. A *RREP*, from the multicast group member, answers the *RREQ*. Figure 3.5(b) shows the *RREP* phase, where the requesting node receives four *RREP*s. In Figure 3.5(c), the most recent and shortest path *RREP* is chosen and the path is established. This *RREP* contains the distance of the replying node from the group leader and the current sequence number of the multicast group. The receiver node then sends a multicast activation (*MACT*) message, confirming to intermediate relaying nodes that they are part of the tree. Nodes wishing to send data to the source and they have no route to it, use a similar procedure. The only difference is that they send a non-join *RREQ* that can be replied by any node with a recent route to the group.

Maintenance: tree maintenance is accomplished by means of an expanding ring search using the *RREQ*, *RREP*, and *MACT* cycle. The downstream node is responsible for issuing a fresh *RREQ* for the group. When a leaf node wishes to leave the group, it sends a prune message upstream, which may be propagated further up the tree. While a non-leaf member continues to be a member of the multicast tree and forwards packets for other multicast receivers, even after it has left the multicast group.

We notice that this protocol integrates unicast, broadcast, and multicast capabilities. Thus information gleaned through the unicast route discovery can be used in multicast route discovery and vice-versa. The information sharing reduces the control overhead and the use of sequence numbers avoids stale routes. On the other hand, the tree-based approach causes poor packet delivery at high mobility, and allows congestion along links in the tree. Also, the used shared-tree is not efficient when the number of multicast sessions increases; it is also susceptible to the failure of a group leader that can severely affect the multicast sessions.

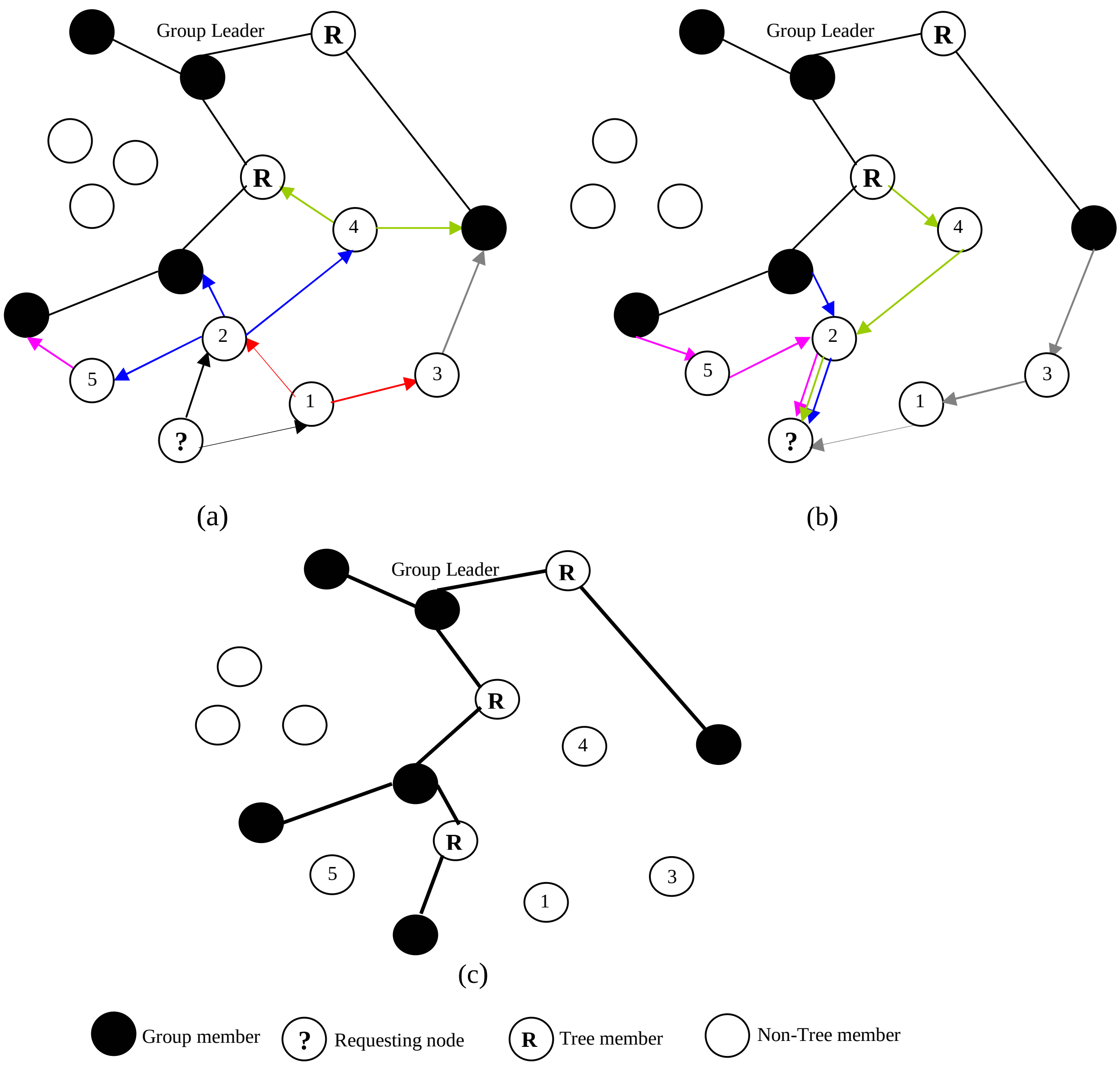


Figure 3.5 Multicast RREQ / RREP Cycle: (a) RREQ Propagation, (b) RREP Propagation and (c) Multicast Tree Creation

3.4.2.1.2 Associativity-Based Multicast (ABAM) Routing Protocol

ABAM [Toh00] Routing Protocol establishes the multicast sessions by utilizing the association stability concept introduced in ABR [Toh97] unicast protocol, aiming to provide more stable paths. Association stability results between two nodes when the number of beacons received continuously from one node to another (i.e. associativity ticks) exceeds a predetermined value, taking into account signal strength and power life of neighbor nodes. ABAM is an on-demand source-tree based multicast protocol, in which a path from source to receiver is constructed based on link stability rather than hop distance.

Operation: the source node initiates the multicast tree construction phase through broadcasting a multicast broadcast query (*MBQ*) message to the entire network. Each intermediate node receiving the *MBQ* appends its ID to this message together with other information (as route relaying load, associativity ticks, signal strength, power life) [Toh97] then rebroadcasts the message. The multicast receiver in its turn collects all the *MBQs* for the multicast group it is interested to join. Then it selects the most stable route among the received *MBQs*, and sends an *MBQ-Reply* back to the source of this route. When the multicast sender receives several *MBQ-Reply* messages from the different receivers, it computes a stable multicast tree that results in shared links then broadcasts an *MC-Setup* message to establish the multicast tree. ABAM allows also a new multicast receiver to join an existing multicast tree. In this case, a new receiver broadcasts a Join-Query (*JQ*) message which functions in a similar way to the *MBQ* message, the on-tree nodes then respond to this query by sending a *JQ-Reply*.

Maintenance: tree reconfiguration takes place when link breakage is detected, where the upstream node of the break broadcasts a Localized Query (*LQ*) message. The affected multicast receiver, on receiving this query, replies by an *LQ-reply* message and the *MC-Setup* message is used again to establish the branch. If the *LQ* message fails, the immediate upstream then starts another *LQ* process. Figure 3.6 demonstrates an example of tree re-establishment. ABAM supports tree deletion and pruning. When a receiver wants to leave the group it sends a *leave* message, and when a multicast group has no more receivers the tree is pruned incrementally. When the source decides to leave the multicast group, the multicast tree can be deleted via sending a multicast *DELETE* message to prune the tree.

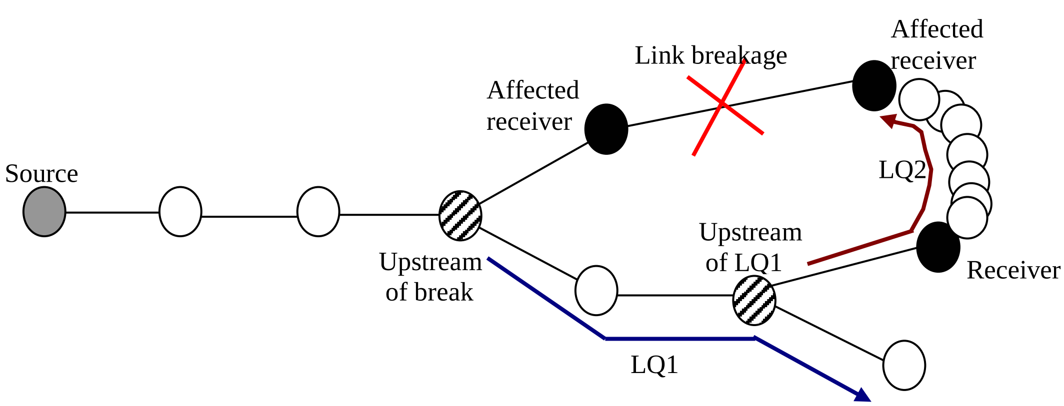


Figure 3.6 ABAM Tree Re-establishment

We notice that in ABAM, the path between a source and a receiver is more stable compared to other multicast protocols, and hence it provides adaptability against mobility and achieves a higher packet delivery ratio. Also, the number of tree reconfiguration and the control overhead are reduced. On the other hand, the increased hop distance between the source-receiver pair makes the protocol less efficient. When there are lots of receivers belonging to the same multicast session nearby, it results in congestion of the most stable paths, which causes a delay increase and a reduction in the packet delivery ratio. Thus ABAM needs employing another technique (as load-balancing) for scalability.

3.4.2.1.3 Adaptive Demand-Driven Multicast Routing (ADMR) protocol

ADMR [Jet01a] is an on-demand source-based protocol, creating source-based forwarding trees to connect each source with the receivers of the multicast group. It tends to modify the multicast tree structure through introducing a forwarding mechanism, based on the shortest-delay path through the tree to the receiver members of the multicast group. A sequence number is included in the packets' header, to uniquely identify the packets and is generated as a count of all flooded ADMR packets.

Operation: a source having a multicast data to be sent starts by flooding the first multicast data packet to the entire network. An *ADMR header* is added to the data packet and a *network flood flag* is set. Setting this flag allows the data packet to be sent to every node in the network. Otherwise, a *tree flood flag* is set, where the packet is only sent to every node in the multicast tree. The source then buffers any subsequent data packets until it receives a valid response, from a potential multicast receiver, in the form of a *Receiver Join* packet. It traverses the reverse path that the original advertisement has taken. As the *Receiver Join* makes its way from the receiver to the source, intermediate routers mark in their routing tables the last hop of the *Receiver Join*. During the original network flood, nodes mark the last hop of the advertisements as their upstream node. By this, nodes are able to create multicast routes. Multicast sources continue to flood periodically the data packet to the entire network. If the application layer at the source stops sending data packets, the source sends a *Keep-Alive* message to the multicast tree. Receivers may also join a multicast group through sending a *Multicast-Solicitation* message to the entire network. The multicast source replies by advancing the time of the next network flood, if it has received several *Multicast-Solicitation* messages within a short period of time. Otherwise, it replies by *Keep-Alive* message down the reverse path. A multicast receiver, receiving a reply from the source, responds with a *Receiver-Join* message, thus completing the three-way handshake and activating the multicast routes.

Maintenance: if a node does not receive data or *Keep-Alive* within a certain time it assumes that the source has finished sending data and it leaves the multicast tree. If neither data packets nor *Keep-Alive* are received at a node before its disconnection timer expires, then it detects link failure and sends a *Repair-Notification* message to its downstream nodes. It then floods the network with a *Reconnect* message. The source sends a *Reconnect-Reply* down the reverse path of the *Reconnect* towards the initiator if it is still interested in sending multicast traffic. Moreover, ADMR defines a pruning mechanism if a lack of passive acknowledgements from downstream nodes occurred.

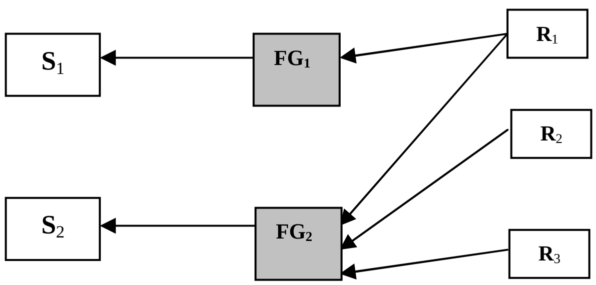
One feature of ADMR is that the nodes are capable of creating or joining a source-specific multicast group. The multicast forwarding state for a given multicast group and a source is conceptually represented as a loosely structured multicast-forwarding tree rooted at the source. On the other hand, a node that lies between the receiver that initiated the *Receiver Join* and the multicast source may receive multiple copies of the *Receiver Join* from several receivers, since no guarantee that the *Receiver Join* will actually reach the multicast source. Also, a node that loses its connection with its upstream node must query the source for a new route. This invokes more control messages, highly increasing the network load.

3.4.2.2 Mesh-based Multicast Protocols

3.4.2.2.1 On-Demand Multicast Routing Protocol (ODMRP)

ODMRP [Lee99] is an on-demand protocol, requiring periodic join/query messages only when sources have data packet to send. One of its unique properties is its unicast capability, where ODMRP can efficiently operate as unicast routing protocol and it can also coexist with any unicast routing protocol. It is a mesh-based protocol, using a mesh structure to connect group members providing richer connectivity, robustness, and supplying path redundancy. A mesh is formed by a set of nodes called forwarding nodes, which are responsible for forwarding data packets between a source-receiver pair.

Mesh initialization phase: to create the mesh, each source in the multicast group floods a join request (*JoinReq*) control packet periodically. A node receiving the *JoinReq* performs a backward learning by storing the upstream node identifier, and then it rebroadcasts this packet. The process continues until reaching the destination (multicast receiver), which broadcasts a join reply (*JoinReply*). Figure 3.7, gives an example of the *JoinReply* forwarding process, taking place between S_1 and S_2 source nodes and the receivers R_1, R_2, and R_3. This message broadcasts a table, with sender node and next node fields in each entry, to establish and update group membership and routes [Lee00b]. A node receiving a *JoinReply* checks if the next node ID in one of the table's entries matches its own ID, then it considers itself as a forwarding group (*FG*) node. The reply forwarding process continues until reaching the source through shortest path building a mesh of *FG* nodes.



R_1 JoinReply

Sender	Next node
S_1	FG_1
S_2	FG_2

FG_1 JoinReply

Sender	Next node
S_1	S_1

R_2 JoinReply

Sender	Next node
S_2	FG_2

FG_2 JoinReply

Sender	Next node
S_2	S_2

R_3 JoinReply

Sender	Next node
S_2	FG_2

Figure 3.7 Join-Reply Forwarding

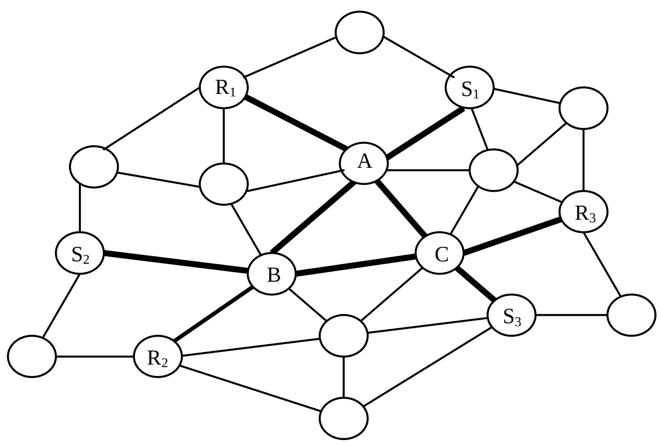


Figure 3.8 Mesh Configuration

Mesh maintenance phase: the multicast mesh protects the session from being affected by nodes' mobility through the paths redundancy, as illustrated in Figure 3.8. For example, during data transmission between S_1 and R_3, if node *B* moves the receiver can still receive data through another path via node *C*. ODMRP uses a soft state approach to maintain the mesh through employing a mesh refreshment mechanism in which the source periodically floods the *JoinReq* control packet.

One of ODMRP key advantages is its unicast capability, where a network equipped with ODMRP does not require a separate unicast protocol. Also, the soft state mesh maintenance approach provides robustness but at the expense of high control overhead. Another disadvantage is that the same data packet propagates through more than one path to a destination node, resulting in an increased number of data packets transmissions, thereby reducing the multicast efficiency.

3.4.2.2.2 PatchODMRP

PatchODMRP [Lee01] extends the ODMRP protocol providing a more efficient way to deal with small number of multicast sources and high mobility. In ODMRP when the number of multicast sources is small, the forwarding mesh is sparse and redundant paths may be unavailable, thus it can be vulnerable to mobility and frequent reconfigurations are required causing large control overhead. To guarantee high data delivery ratio in this case, the *JoinReq* interval has to be set shorter with larger mobility. This short interval causes a lot of control overhead. PatchODMRP deploys a local patching scheme instead of frequent mesh reconfiguration, where it copes with mobility without reducing the *JoinReq* interval. This takes place through performing a local recovery scheme when some parts of the mesh are locally disconnected.

Operation: Figure 3.9, gives an example of the protocol's operation. The traditional ODMRP mesh is shown in Figure 3.9(a), connecting the multicast source *S* to the multicast receiver *R*. Each *FG* node utilizes MAC layer to check for its neighbors, comparing this information with the upstream *FG* node information in its forwarding table to detect if there is an upstream *FG* node that is not reachable. In Figure 3.9(b), node *K* detects that node *J* is unreachable as a result of the failure of the link *JK*. At this case, *K* starts the patching procedure by flooding advertisement message (*ADVT*), advertising the upstream loss. The lifetime of this packet is set to a very small value to limit the flooding scope and to perform it locally. If *J* supports more than one multicast groups, then it is added in the *ADVT* packet. A node receiving the *ADVT* packet updates its routing table entries for the source of the *ADVT*. In Figure 3.9(c), a *PATCH* packet is generated as a reply on the *ADVT* and is forwarded *I* to *K*, selecting *L* as a temporary *FG* node. If *K* receives more than one *PATCH* packet, it selects the shortest path to the multicast source. The new mesh path is illustrated in Figure 3.9(d), where *K* marks *L* as a new upstream *FG* node.

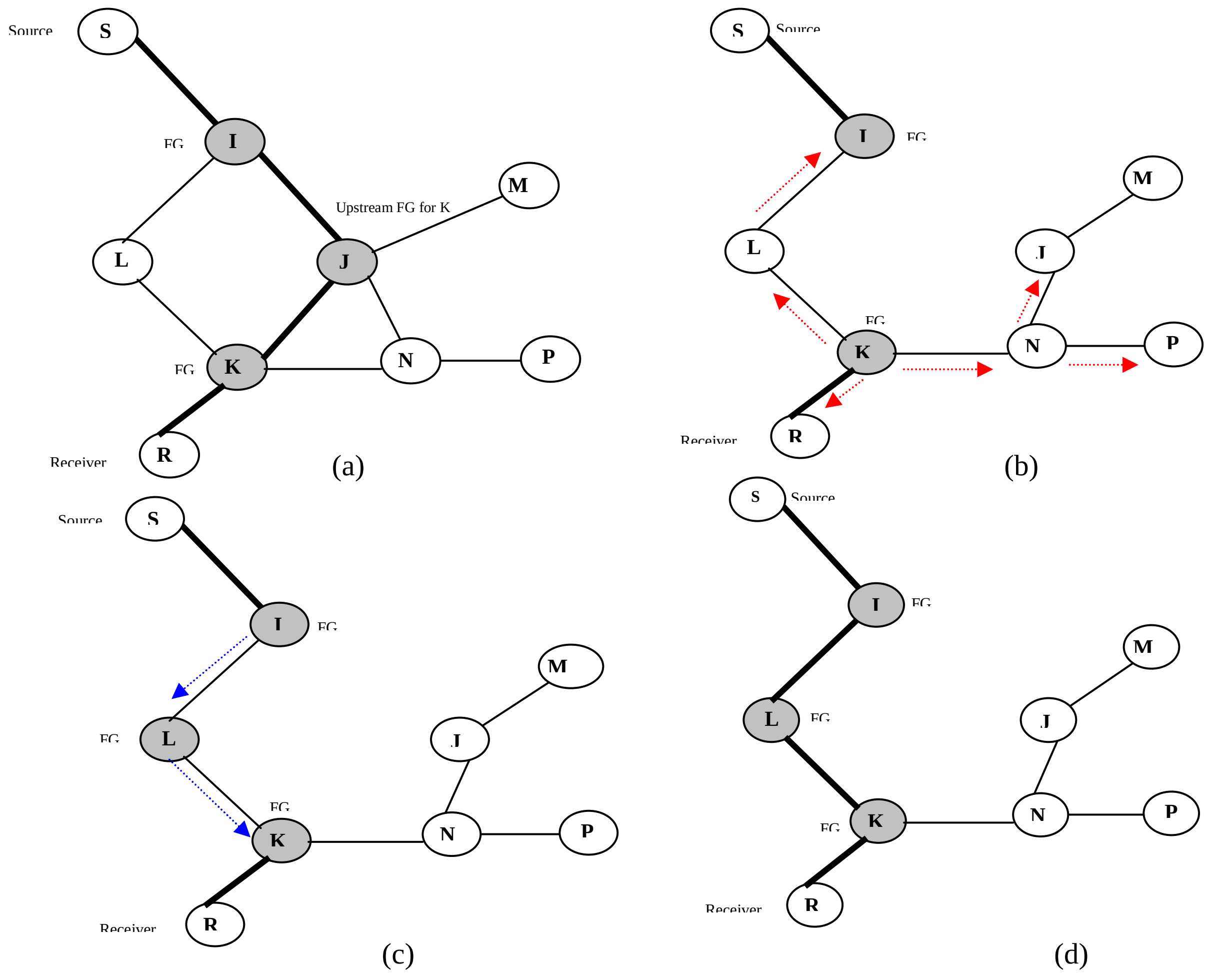


Figure 3.9 Example of PatchODMRP Operation: (a) ODMRP mesh, (b) J unreachable from K, (c) PATCH packet from I to K and (d) K marking L as FG node

3.4.2.2.3 Forwarding Group Multicast Protocol (FGMP-RA)

Forwarding group multicast protocol (FGMP-RA [receiver-advertising]) [Chi98] is a mesh-based protocol based on the forwarding group concept. Its major difference with respect to ODMRP is that, it is a receiver-initiated protocol while ODMRP is a source-initiated protocol.

Mesh initialization phase: each receiver floods the *JoinReq* control packet in the network. Each source receiving these *JoinReq* packets, updates its member table to keep the IDs of all the multicast group receivers, and creates a forwarding table sending it towards the receivers. When the forwarding table reaches the receivers, the routes between the source-receiver pairs become established.

Mesh maintenance phase: a soft state approach is used for routes' maintenance. Receivers periodically flood the *JoinReq* packets to refresh the routes. In case of link failure, the source replies to the *JoinReq* packets by transmitting the forwarding table on the new existing routes.

This protocol is considered more robust than the tree-based protocols, however the soft state maintenance approach increases the control overhead. This protocol is more useful when the number of sources is greater than the number of receivers.

3.4.2.2.4 Core-Assisted Mesh Protocol (CAMP)

CAMP [Gar99] uses core nodes in the mesh to eliminate the flooding approach used in ODMRP and FGMP-RA during the mesh creation and maintenance. Thus, it is more efficient in bandwidth utilization. CAMP assumes the existence of an underlying unicast routing protocol in the network environment, which provides the next node ID.

Mesh initialization phase: CAMP is a receiver-initiated multicast routing protocol. Initially, to join the mesh, a receiver extracts the core node ID from its core-to-group address table and unicasts a *JoinReq* packet toward this core node. In forwarding the *JoinReq*, the next node is obtained by using the underlying unicast protocol. When a mesh member node receives this *JoinReq*, it sends an *ACK* to the receiver, and thus it becomes a part of the multicast group. The *JoinReq* packet may not be sent if a receiver wishes to join a mesh and it has a neighbor node already present in the mesh. In this case, the receiver joins the multicast group via announcing its membership using *Multicast Routing Update* message and modifying the multicast routing table.

Mesh maintenance phase: link failures are not very critical in CAMP. Each receiver losing a path on the mesh uses a *Push Join* message to establish a new path. CAMP ensures partition repair by means of the *Core Explicit Join* message that is sent by each active core in the mesh component to the cores in the other mesh components. The partition is repaired when a core receives a *Core Explicit Join* message and replies with an *Ack* message.

We notice that, by avoiding the flooding approach, CAMP allows a lower control overhead. Still, core node failures cause significant packet losses. Another drawback of this protocol is that it is not standalone, as it needs the support of an existing unicast routing protocol that should work correctly in the presence of core failures and network partitions. Thereby, not all routing protocols could be compatible with CAMP.

3.4.2.3 MANET Recently Proposed Multicast Protocols

MANETs propositions concerning multicast routing in ad hoc networks are few. As we mainly focus in this chapter on on-demand multicast protocols, we present two of the MANETs recently proposed protocols in this approach.

3.4.2.3.1 Multicast Routing Protocol Based on Zone Routing (MZR)

MZR [Dev01] is a source-initiated on-demand protocol. It creates source-based multicast trees using the concept of zone routing. For each multicast session, a delivery tree rooted at the source is created on-demand. MZR defines zones by the nodes' local neighborhood, specified by the zone radius in terms of number of hops, where the flooding of control packets by each node are controlled by using the zone routing mechanism [Haa01].

Operation: MZR employs a proactive protocol inside each zone to maintain at each node an up-to-date zone routing table, and a reactive multicast tree creation by the source. Initially the source sends a *Tree-Create* packet to each node in its zone, identified by the multicast session ID. Each intermediate node receiving the packet creates a route reverse entry in its multicast routing table with the empty list of downstream set, and the upstream is set to the node from which *Tree-Create* was received. Thus, any zone node interested in joining the session replies by a *Tree-Create-Ack* through the created reverse route to the source. During the *Ack* forwarding, each node along the path updates its corresponding routing table entry downstream. Once the source is done with its zone, it begins to extend the multicast tree to the entire network, through sending a *Tree-Propagate* message to each border node of its zone. Each border node, receiving this message, creates a multicast route entry for this session and begins to send *Tree-Create* to each node in its zone. The same process then takes place in the border node zone until each mobile node gets a *Tree-Create* packet.

Maintenance: a tree refresh mechanism is used to maintain up-to-date multicast routing information at each tree member node, through sending a *Tree-Refresh* packet by the source during the multicast session. MZR reacts to link breakage when the downstream nodes detect this. A downstream node then initiates branch reconstruction via sending *Join* packets first to all nodes in its zone, where any multicast tree member node with a valid route entry can reply with a *Join-Ack*. If no *Join-Ack* is received, then a *Join-Propagate* message is sent to the downstream border nodes, until a *Join-Ack* is received. PRUNE messages are also used to allow nodes to leave the multicast session when they wish.

MZR reduces the control overhead as it runs over ZRP, showing the efficacy of the zone-based approach in multicast routing. Also, the link repair mechanism has advantage of localizing branch reconstruction if the initiator node finds a multicast tree member in its zone. A disadvantage of this protocol is that a far located receiver node needs to wait for a long time before it can join the multicast session, as the propagation of *the Tree-Propagate* message takes a considerable amount of time.

3.4.2.3.2 Simple Multicast and Broadcast Protocol (SMBP)

The simple multicast and broadcast protocol [Jet01b] is derived from unicast DSR routing protocol, where it utilizes the DSR route discovery mechanism. It can be implemented as a standalone protocol and used independently of DSR. This protocol does not need multicast setup (explicit establishment) in the network for data delivery.

Operation: a node wishing to send a broadcast data packet uses the same DSR route discovery mechanism piggybacking the data packet in the *RREQ*, which is flooded into the network. A multicast data packet is also flooded using the same approach with the multicast group as the *RREQ* target. When a multicast receiver receives this *RREQ* it makes a copy of the included data packet and passes it up to the protocol stack (to data layer) before forwarding. *RREQ* is transmitted with the multicast or broadcast address as the target of the route discovery. It proceeds in a similar way to DSR with the constraint that it should not be rate limited, and should be always permitted (i.e. non propagating *RREQ* is not allowed in this protocol). Route cache should not also be consulted on behalf of the *RREQ* with multicast and broadcast targets.

As we notice, this protocol does not need a multicast setup, and hence it is useful in applications of very high mobility where rapid topology changes are difficult to track. It is also useful in network of relatively small number of nodes, in which the overhead of keeping multicast state exceeds the overhead of flooding.

3.4.2.4 Specific-Purpose Multicast Protocols

As mentioned in Section 3.4.1, there are some multicast routing protocols that are designed to provide different user needs depending on the scenarios in which they are used. In this section, we discuss two of these protocols.

3.4.2.4.1 Role-Based Multicast (RBM)

RBM [Bre00] is a multicast scheme designed to meet the special needs of inter-vehicle communication. The multicast group changes dynamically, in such environment, based on the vehicle location, speed, driving direction, and time. An application example of this scheme is the accident situation on highways, where information about the accident should be disseminated to the relevant vehicles (receivers). Operation takes place, through flooding information about the accident using a modified flooding technique that considers the speed, direction of movement, distance from the accident source (multicast source). This calculates a dynamic multicast group including the vehicles for which the disseminated information is useful, so that the drivers can break their vehicles before the accident zone. We notice that this protocol considers a stationary source and high-speed mobile receivers, mostly towards the source.

3.4.2.4.2 Content-Based Multicast (CBM)

CBM [Zho00] is used in areas where the source set and the receiver set for the information keep changing dynamically based on the content of the information and the mobility of the receivers themselves. An application example for this scheme is in the battlefield where the moving soldiers need to be continuously updated on the impending threats that may occur within certain duration or that may be present at a certain distance from them. However, the main problem in such applications is the difficulty for the information sources (multicast source) to determine their receiver set (multicast receivers), and it is also difficult for the receiver nodes to determine the identity of the sender. This is due to the fact that the nodes and the threats keep moving all the time. The solution proposed in CBM is based on a *sensor-push* and *receiver-pull* approach, dividing the entire area into geographical regions called blocks, with a block leader in each block. The operation takes place through scattering sensor nodes in each block to gather information about the threats and forward them to the block leader. The block leader may further forward this information to other blocks depending on their location from the threats as well as the threats velocity. On the other hand, each receiver node sends a *PullRequest* message to the leader of the block in which it is expected to be present after a time period *t*. The block leader either replies directly to the receiver if it has the required information about the threats, otherwise, it sends itself a *PullRequest* to the leaders of other blocks in the direction of the threats in order to forward complete information to the requesting receiver.

3.5 Discussion and Conclusion

In this chapter, we studied the problem of multicast routing protocols in ad hoc networks, introducing the major challenges faced in the design of these protocols. We also identified the main issues required in the design of an efficient ad hoc multicast routing protocol, providing different classifications for the existing multicast routing protocols in ad hoc networks. We also described in details several multicast routing protocols according to our provided classifications, stating their advantages and limitations. Table 3.1, summarizes our previous discussion for these protocols, illustrating some points of comparison between them.

Concerning the tree-based protocols, they suffer from a considerable overhead during tree maintenance and link breakage recovery, requiring a lot of control messages and wasting resources. As a means of routing performance improvement, stability of links was proposed as a criterion during the routes establishment. However, this method reduces the routing efficiency due to the increase in the hop distance between the source-receiver pairs. Also, a congestion of the most stable paths may occur when there are lots of receivers belonging to the same multicast session near by. On the other hand, the mesh-based protocols provide more robustness against mobility and save the large size of control overhead used in tree maintenance. However, most protocols of this type rely on frequent broadcasting, which may lead to a scalability problem when the number of sources increases. Furthermore, they may form sparse mesh and unavailability of redundant paths, when the number of sources is small. Consequently, frequent reconfigurations may be required to recover link breakage increasing the control overhead, which becomes more prominent in this case. In spite of the multicast topology (tree or mesh), we observe that the shortest path is mostly used as a base criterion in routes establishment. This fact does not always provide the optimal routes in a dynamic network as ad hoc network. Other important criteria should be considered (as path stability, power efficiency, link quality, topological changes, interference). The choice of a routing path should be adaptive to the dynamic environment while considering these factors.

Table 3.1 Comparison of Different Multicast Protocols

	MAODV	**ABAM**	**ADMR**	**MZR**	**ODMRP**	**Patch ODMRP**	**FGMP-RA**	**CAMP**
Multicast Topology	Shared-Tree	Source-Tree	Source-Tree	Source-Tree	Mesh	Mesh	Mesh	Mesh
Routing Approach	On-demand	On-demand	On-demand	On-demand	On-demand	On-demand	On-demand	On-demand
Dependency on Unicast Routing	No	No	No	Yes	No	No	No	Yes
Periodic Control Messages	Yes	No	Yes	Yes	Yes	Yes	Yes	No
Control Overhead /Flooding	At tree construction and maintenance	At tree construction and link repair	At tree construction and maintenance	Tree refreshment only	At mesh construction and maintenance	At mesh construction only	During the Jon Request Flood	Mainly at first time of receivers join and network partitions
Multicast Session Initialization	Receiver-initiated	Source-initiated	Source-initiated	Source-initiated	Source-initiated	Source-initiated	Receiver-initiated	Receiver-initiated
Route Construction Metric	Freshest and shortest path	Tree and link longevity	Freshest and shortest path	Nearest hops path	Shortest path	Shortest path	Mainly shortest path	Based on the underlying unicast protocol
Security Support	No	No	No	No	No	No	No	No

We noted that multicast routing is a young research domain, no standard has been adopted yet and many issues have to be addressed and more studies are needed. Also, performance studies are not completely finalized and analytical studies are being complex. The validation of the presented mechanisms is being mainly conducted through simulations. These facts have raised our motivation in providing optimal communication abilities in multicast ad hoc routing. Consequently, we proposed a multicast routing protocol for mobile ad hoc networks, named Source Routing-based Multicast Protocol (SRMP) [Mou04]. Chapter 5 gives a detailed explanation for this protocol.

Following our study and investigation, we can conclude that reliable multicasting is critical for the successful deployment of ad hoc networks that support important multicast applications. The ad hoc multicast routing is still a young research domain with respect to unicast routing. Up till now, the propositions in this subject are scarce compared to unicast routing, and they lack standardization. Accordingly, multicasting in ad hoc networks is a significant problem that merits further exploration.

Beside our contributions in the multicast routing in ad hoc networks, we also investigated the unicast routing problem. In the next chapter, we propose an energy efficient unicast mechanism, EC-DSR, evaluate its performance and compare it with DSR.

CHAPTER 4 ENERGY CONSERVING DYNAMIC SOURCE ROUTING (EC-DSR) PROTOCOL

Building ad hoc networks implies a significant technical challenge because of many constraints, such as limited energy consumption, unreliable wireless links, and dynamic network topology. An important trade-off lies between link maintenance in a highly unreliable network and power conservation for users with little battery power. In this chapter, we focus on power optimization through efficient routing techniques in MANETs.

Routing protocols must have the ability to react quickly to link failures, and at the same time, should reduce the amount of unnecessary routing overhead aiming to conserve energy. From this perspective, power-aware routing should be vastly considered.

Our goal in this subject is to exhibit new characteristics in ad hoc routing in order to provide efficient saving in bandwidth and network resources, and to insure minimum energy consumption along the different used routes. In this context, we propose the Energy Conserving Dynamic Source Routing (*EC-DSR*) protocol.

We present a state of the art on energy efficient routing in Section 4.1, and a detailed description of EC-DSR protocol in Section 4.2.

4.1 Energy Efficient Routing in Ad hoc Networks: state of art

As previously mentioned, routing protocols design in ad hoc networks faces several constraints, with the nodes' battery dependence as a chief constraint. An important issue is to optimize and conserve as much power as possible while still achieving good links quality. Hence, energy efficient routing protocols and mechanisms are needed, to maximize the network lifetime and increase the network survivability.

There has been considerable research on energy conserving. Much of this research has focused on packet transmission, at the link layer, and routing protocols at the network layer. In this section, we present a brief overview on the most relevant energy conserving routing protocols, as it is the focal point of our work in this chapter, and hence we illustrate the motivation for our contribution in this subject.

A number of routing proposals took the energy conservation into consideration in order to extend the lifetime of the wireless nodes through wisely using their battery capacity. In this context, few routing mechanisms have been proposed, addressing the energy constraints problem and focusing on providing efficient power utilization. The Minimum Total Transmission Power Routing (*MTPR*) protocol [Can02] was developed to minimize the total transmission power consumption of nodes participating in the acquired route. It performs the route selection by calculating the nodes' transmission power (P_{MTPR}), as illustrated in Equation 4.1;

$$P_{MTPR} = \min_{R \in S} P_R \tag{4.1}$$

S: set containing all possible routes
P_R: transmission power for the route R
P_{MTPR}: transmission power for the selected route

Transmission power required to have successful reception at the receiver has to be proportional to some power of the distance between the transmitter and the receiver. Actually, routes with more hops having short transmission ranges are preferred to those with fewer hops and having long transmission ranges. As a result, more nodes may be involved in forwarding packets leading to an increase in the end-to-end delay from one side and to a more energy waste along the network from the other side. As a larger number of nodes are involved in routing, all nodes that are neighbors to the intermediate nodes will also be affected. Moreover, we notice that this approach does not consider the nodes' remaining power, and thus it fails to prolong the lifetime of each host.

Further proposals considered the nodes' remaining power instead of only reducing the total transmission power. Minimum Battery Cost Routing (*MBCR*) [Sin98] utilizes the sum of the inverse of the battery capacity for all intermediate nodes as the metric upon which the route is selected. However, this approach requires that the summation should be minimal, which allows some hosts to be overused because a route containing nodes with little remaining battery capacity may still be selected. Alternatively, the Min-Max Battery Cost Routing (*MMBCR*) protocol [Can02], treats nodes more fairly from the standpoint of their remaining battery capacity. It considers the remaining power of nodes as the metric for acquiring routes in order to prolong the lifetime of each node, such that smaller remaining battery capacity nodes are avoided and ones with larger battery capacity are favored when choosing a route. Route selection takes place according to its transmission power (P_{MMBCR}), which is calculated in Equation 4.2;

$$\mathrm{P}_{\mathrm{MMBCR}} = \min_{\mathrm{R} \in \mathrm{S}} [\max_{\mathrm{n} \in \mathrm{R}} (1/\mathrm{BatteryCapacity}_{\mathrm{n}})] \tag{4.2}$$

S: set containing all possible routes
n: each node belonging to the route R
P_{MMBCR}: minimum-maximum battery cost for the selected route

However, this approach will consume more overall energy throughout the network since the minimum total transmission power routes are no longer favored.

A hybrid approach, named Conditional Max-Min Battery Capacity Routing (*CMMBCR*) protocol [Toh01] was developed, trying to arbitrate between the MTPR and the MMBCR. It considers both the total transmission energy consumption and the nodes' remaining power. MTPR is used when all the nodes in some possible routes (one route is sufficient) comprise a battery capacity above a so-called battery protection threshold, and MMBCR is used if no such route exists.

In [Gar03], three power-aware routing protocols were developed based on the DSR protocol: these are respectively *MDR*, *LEAR*, and *EDDSR* protocols. Firstly, the Minimum Drain Rate (*MDR*) mechanism, as its name implies, proposes the drain rate as a new metric, to be used in conjunction with the residual battery capacity in predicting the nodes' lifetime according to the current traffic conditions. Nevertheless, the drain rate is not always a wise metric in an ad hoc environment, as it is much tied to a fixed infrastructure. Secondly, the Local Energy-Aware Routing (*LEAR*) was proposed as a power aware route selection mechanism with the goal of equally balancing the total energy consumption among all nodes in the network. It distributes the decision of nodes' cooperation, in forwarding packets, among all nodes in the network. However, distributing the decision of forwarding packets among all nodes in the network may rise the notation of selfish nodes and in its turn allows the denial of service occurrence, which threatens the routing efficiency. Finally, the Energy Dependent DSR (*EDDSR*) mechanism comes as a power aware optimization applied to the route discovery process of DSR. It tries to avoid the use of weak battery power nodes, using information related to the residual energy in the route discovery procedure. Whereas, each node determines its willingness to participate in forwarding packets based on its current energy level. Nevertheless, the dependence on the current energy level as a sole factor may not be sufficient in all the cases, as it does not assure any link availability among the nodes of higher energy level. The selected routes in this case may then be exposed to more link failures, which consume more energy in its turn during the maintenance process.

Three extensions to AODV are also proposed in [Sen04], considering energy consumption during the route discovery process. In the first extension, named Local Energy-Aware Routing based on AODV (*LEAR-AODV*), each mobile node relies on local information about its remaining battery level to decide whether to participate in the selection process of a routing path or not. This allows energy-hungry nodes to conserve their battery-power by not forwarding data packets on behalf of the other nodes, which may raise to a certain extent the notation of nodes' selfishness or denial of service. The second extension in this work is the Power-Aware Routing based on AODV (*PAR-AODV*). Its main objective is to extend the useful service life of an ad hoc network. PAR-

AODV, tries to find a route *R* at route discovery time *t*, while minimizing the cost function, as calculated in Equation 4.3;

$$C(R, t) = \sum_{i \in R} C_i(t) \tag{4.3}$$
$$C_i(t) = \rho_i \, [F_i / E_i(t)]^{\alpha}$$

ρ_i : transmission power of node *i* ;
F_i : full charge battery capacity of node *i* ;
$E_i(t)$: remaining battery capacity of node *i* at time *t* ;
α : a positive weighting factor

As the cost function exploits the minimal sum idea, it allows some hosts to be overused due to the repetitive selection of some routes containing these hosts. The third extension proposed in this subject is the Lifetime Prediction Routing based on AODV (*LPR-AODV*). This extension favors the route with the maximum lifetime, or in other words the route that does not contain nodes with a weak predicted lifetime. It finds a route *R*, at route discovery time *t*, while maximizing the value function illustrated in Equation 4.4;

$$Max_R[T_R(t)] = Max_R \, [Min_{\, i \in R} \, (T_i(t))] \tag{4.4}$$

$T_R(t)$: lifetime of the path *R*;
$T_i(t)$: predicted lifetime of node *i* in path *R*

This approach predicts the battery lifetime at each node through estimating its past activity in transmitting and forwarding packets. Each node uses its recent history as an indicator of the traffic crossing it. However, this lifetime prediction approach does not outfit in an ad hoc environment. As previously mentioned, it is difficult to extract a constant pattern for the traffic path in such network, especially if it encompasses a high degree of mobility.

The study in [Cha03] proposes a new energy aware routing protocol, which tries to increase the energy resource durability. The proposed protocol, named Energy Conserving GRID (*ECGRID*), exploits the concept of a routing protocol called *GRID* [Lia01] while considering the energy constraints. In GRID, the graphical area of the entire MANET is partitioned into 2D logical grid. Routing is performed in a grid-by-grid manner, and a mobile host will be elected as the gateway for each grid. ECGRID considers the energy of mobile hosts, such that for each grid one mobile host will be selected as the gateway and the others can go to sleep mode. In fact, this mechanism boasts unfair energy consumption among the mobile nodes. We notice that the gateway nodes' power is susceptible to exhaustive energy consumption, especially in large grids' size.

We also noticed that introducing virtual infrastructure takes place in this subject, aiming at energy conserving. An architecture for wireless mobile ad hoc networks, named Power-Aware Virtual Base Stations (*PA-VBS*), is proposed in [saf01]. It proposes electing a mobile node from a set of nominees to act as a base station within its zone based on its residual battery capacity as well as on a couple of energy thresholds. However, this scheme does not fit well neither in a network of scalable number of nodes nor in a highly mobile network. The former causes the selected virtual base stations to be charged with a large capacity of processing and hence leading to a great waste in energy and rapid *VBS* failure. While the latter, introduces the difficulty of the continuous *VBS* selection due to the high network mobility, and thus it does not fit in an ad hoc environment.

Throughout this section, we presented a review on power efficient routing techniques, demonstrating various algorithms and mechanisms that try to minimize the power consumption during the routing process aiming to maximize the lifetime of the network. We noticed that most of the proposed energy conserving protocols and mechanisms are confined within specific approaches. Some approaches introduce the sleep mode to save battery resources; others try to minimize the transmission power consumption and/or consult the nodes' remaining power during their routing procedures. Furthermore, some approaches introduce the notion of infrastructure to provide a backbone dedicated to most of the processes that highly consume energy.

Actually, introducing the sleep mode increases the probability of losing packets when the destination host is in the sleep mode. Minimizing the total transmission power, involves more forwarding nodes. This results in an increase in the end-to-end delay and the probability of link failures. And the use of nodes' remaining power does not always assure fair traffic distribution. Also, the dependence on a designated backbone opposes to a certain limit the "on-the-fly" notation of the ad hoc networks.

In our approach, we seek several criteria in order to assure energy conserving. Rather than focusing only on the power resources of mobile nodes, we extend this idea considering other important factors. For example, the stability of nodes as well as the links' quality may influence the energy consumption. The lack of these factors exposes the network to many packets loss and requires several re-transmissions consuming more power and bandwidth resources.

4.2 Description of EC-DSR

Our goal is to provide new characteristics in ad hoc routing to provide efficient saving in bandwidth and network resources, and to insure minimum energy consumption along the different used routes. We propose the Energy Conserving Dynamic Source Routing (EC-DSR) protocol [Mou03a, Mou03b] to achieve path adaptability and energy conserving. The former provides robustness against host mobility and adaptability to wireless channel fluctuations. While the latter aims to increase the durability of the power resources, which increases the lifetime of the nodes and the whole MANET. Furthermore, EC-DSR attempts to minimize both routing and storage overhead by providing optimization of network resources use, especially in large-scale networks. Our mechanism can be applied to any on demand routing protocol using a route-discovery phase. In this work, we apply it to DSR.

EC-DSR constructs its routes employing a selected set of stable energy-conserving nodes with high quality links. Nodes are selected according to four criteria: *level of battery power* at each node, *nodes' stability* with respect to its neighbors biasing the route selection towards routes with relatively stationary nodes, *quality of the link* between nodes in terms of the received signal level, and *links' availability* using future prediction for the links' state.

This approach discharges low battery power nodes in an adaptive mean. In addition, it applies the concept of connectivity quality during the nodes selection via considering nodes' stability, energy conservation, links' availability and higher quality. To our knowledge, the majority of routing protocols at the time of our proposition used only one metric during their routes construction.

4.3 EC-DSR Operation

We applied our proposed energy conserving mechanism on DSR unicast protocol [Joh96], modifying its route discovery process. This mechanism can be applied on any unicast routing protocol employing a route discovery.

Firstly, we used the MAC layer beacons to provide each node with its neighbors' existence as well as stability information about each existing neighbor. When a node receives a neighbor's beacon, it updates or creates the corresponding entry of this neighbor in its *Neighbor_Table*, see Table 4.1. Through each beacon reception from every neighbor, the node executes three updates in its *Neighbor_Table*. Firstly, the node initiates or increments a stability counter towards the corresponding neighbor, indicating the level of association between itself and this neighbor. Secondly, the node records the strength of the received beacon from the corresponding neighbor indicating the quality of the link between them. Third update concerns the link availability between the node and the corresponding neighbor. At each beacon reception from a certain neighbor, the node predicts the link availability between them through applying a probabilistic model [McD99] for future prediction of link's state, given that the link currently exists. The link's availability takes the form of a probabilistic value, which is stored in the *Neighbor_Table* towards the corresponding neighbor.

Table 4.1 EC-DSR Neighbor Table

Neighbor	Type	Stability	Signal Strength	Link Availability

Concerning the energy consumption, we invoke an energy model to calculate periodically the energy (battery) level value at each node ($\mathbf{B_j(t)}$). We assume that this value is stored in the nodes' data structures and is updated periodically. Our energy model considers the energy consumed by packet transmission, packet reception, and during the idle state (see Equation 4.5). It is assumed that all nodes start with the same initial energy.

$$B_j(t) = B_j(current) - [E_{tx} + E_{rx} + E_{idle}] \quad , 1 \leq j \leq N \qquad (4.5)$$

- B_j(current) : Current battery power [Initially, Bj(current) = Bj(0)];
- E_{tx}: total energy consumed for each transmitted packet (including processing and transmission);
- E_{rx}: total energy consumed for each received packet (including reception and processing);
- E_{idle}: total energy consumed by each node in the idle state (monitoring the channel for any incoming packets);
- N: Total number of nodes.

Operation starts when a source node has data to transmit to a certain destination and it has no route to that destination. The route discovery procedure is then invoked searching for the destination. Route discovery starts through transmitting a *request* packet to a selected set of neighbors **{**$\mathbf{nb_i}$, $1 \leq i \leq N-1$, N: total number of nodes**}**. This set of neighbors is selected to forward the *request* packet such that each neighbor satisfies the following four conditions:-

(i) The battery level of the selected node (Battery(nb_i)) ≥ Bthreshold(t); t is the current time;
(ii) The stability between the selecting node and the selected neighbor (Stability(n, nb_i)) ≥ Sthreshold;
(iii) The strength of the signal between the selecting node and the selected neighbor (Signal_Strength(n, nb_i)) ≥ SSthreshold;
(iv) The availability of the link between the selecting node and the selected neighbor (Link(n, nb_i)) ≥ Lthreshold

The Sthreshold, SSthreshold, and Lthreshold are fixed values, which are experimentally achieved. The Bthreshold(t) is a variable threshold as a function of time. We did not fix its value, as the battery consumption is a function of time even in the idle cases.

Figure 4.1 gives an example of the route discovery phase in a small network, consisting of one source (node *S*) and one destination (node *D*). As shown in Figure 4.1(a), *S* starts transmitting a *request* packet to the selected neighbors 2 and 4. In turn, nodes 2 and 4 start their neighbor selection process and forward the *request* to their selected neighbors. The process continues until reaching the destination (node *D*). Meanwhile, the source route accumulates in the *request* packet during its forwarding among the selected nodes.

The selection procedure takes place in a recursive manner until reaching the destination following our connectivity quality criteria among the neighbors. A destination receiving a *request* packet takes a copy of the accumulated route in its header and transmits a *reply* packet in the reverse route direction. The *reply* packet continues to be forwarded along the source route that is stored in the packet header, carrying the selected nodes, until reaching the source. This process constructs routes between the source and the destination consisting of selected nodes to forward data. Figure 4.1(b), gives an example of the *reply* transmission and forwarding to construct the routes between the destination *D* and the source *S*. As shown in the figure, two routes are constructed, which are respectively [*S-4-7-10-D*] and [*S-2-5-6-9-D*].

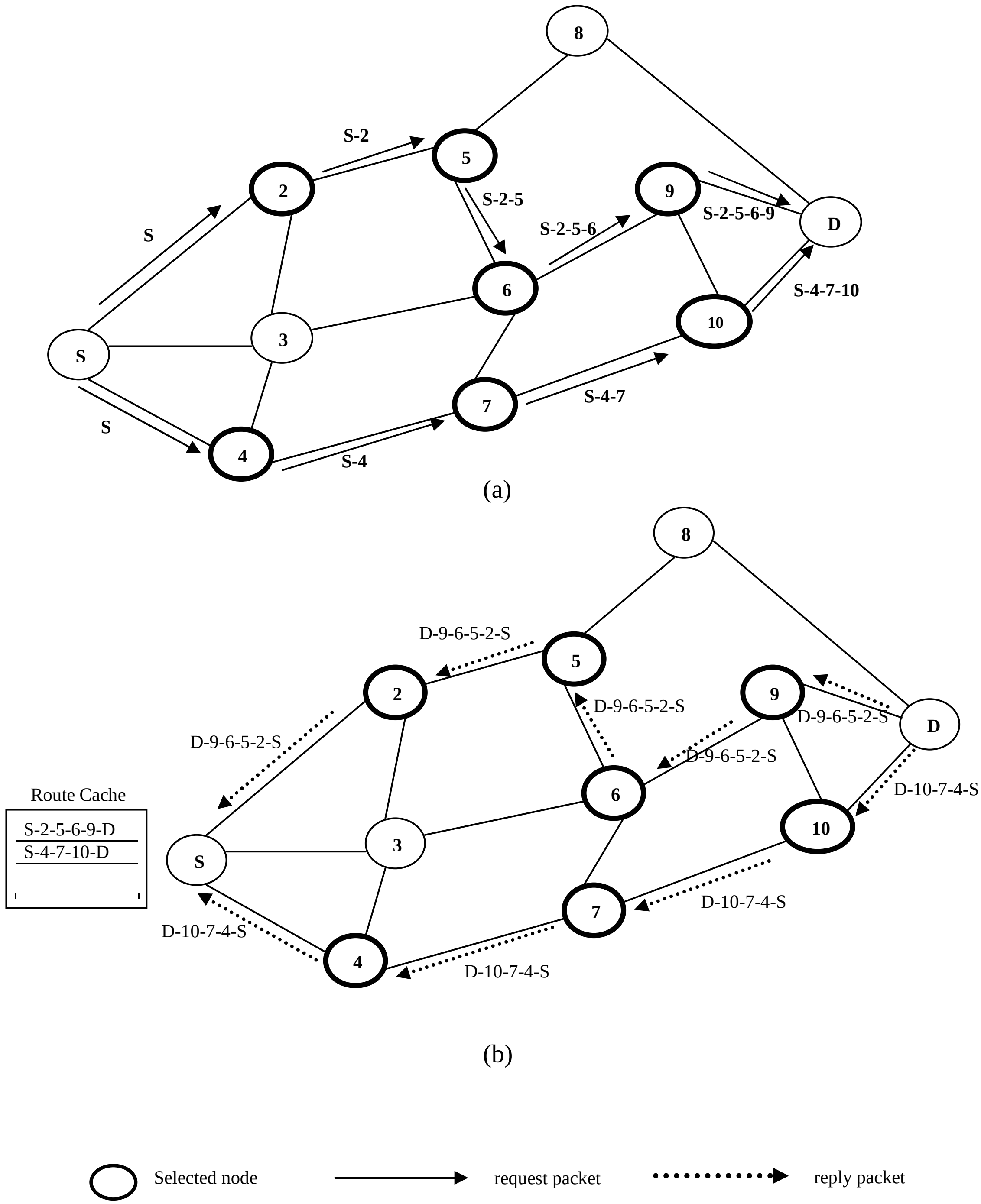


Figure 4.1 An Example of the Request/Reply Processes in a Small Network: (a) Route Discovery Process, (b) Route Reply Process

The source receiving the *reply* packet, stores in its cache the route, which is found in the packet header. Then, the source selects the shortest path route from its routing cache to transmit its data. Figure 4.2, indicates the data transmission from the source *S* to the destination *D*, on the selected path from the route cache, according to the shortest path criterion.

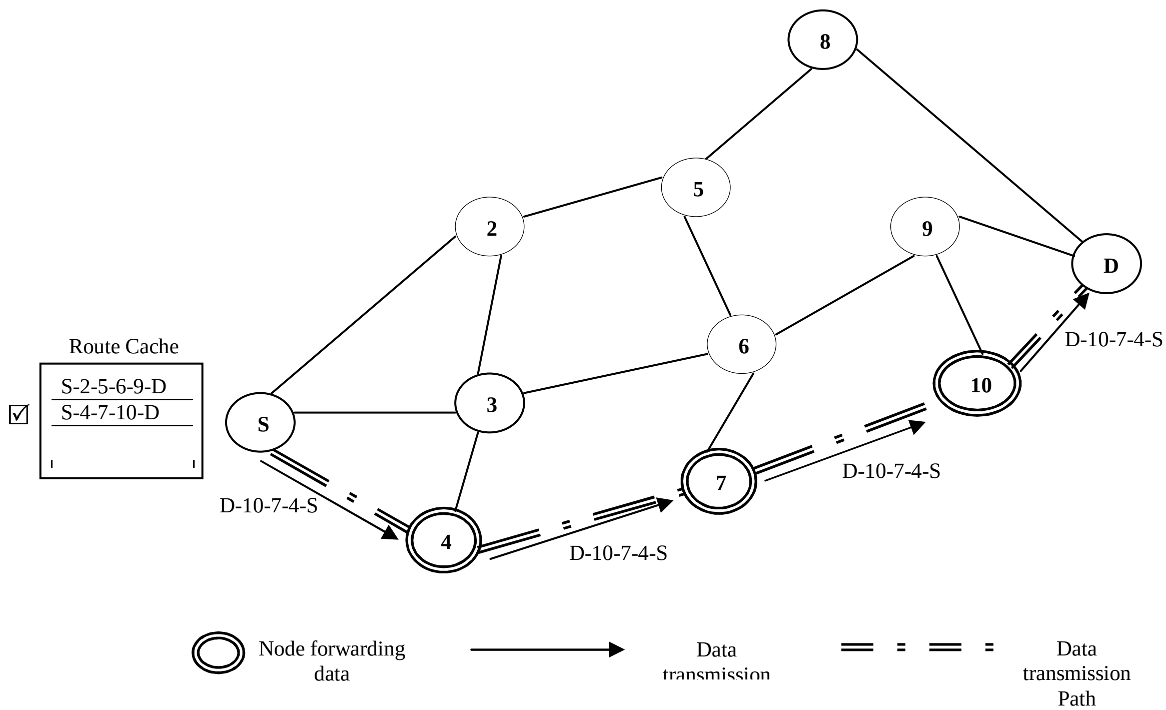


Figure 4.2 Data Transmission from S to D

4.4 Performance Evaluation

In this section, we evaluate the performance of our proposed scheme via simulation. We compare its performance to DSR protocol, illustrating the performance improvements thanks to the energy conserving mechanism. Actually, we applied two approaches in our evaluation study; firstly, we study the behavior of EC-DSR at different mobility types for small, medium, and scalable networks' size. Better results are obtained in favor of the EC-DSR in terms of the control overhead, as well as significant improvements in delay and forwarding efficiency for large scalable networks. Then, we use pragmatic node mobility models in our performance evaluation. Since grouped motion behavior is likely to occur in an ad hoc network, we evaluate the EC-DSR performance employing two group mobility models, the Pursue model and Reference Point Group Mobility (RPGM) model. We analyze the EC-DSR performance with these two models and we compare it to the obtained performance with the Random Way Point (RWP) mobility model. Consequently, we illustrate how the performance criteria of our protocol can be highly affected by the mobility models' features.

Detailed simulations are carried out under network simulator (*ns*-2), a discrete event simulator developed at Berkeley University targeting at network research [Fall98].

4.4.1 Simulation Model and Scenarios

The overall goal of our simulation study is to analyze the behavior of our protocol under a range of various networks' size and mobility scenarios. We run our simulations using a MANET composed of (20, 25, 50, 75, 100) nodes. The radio and MAC layer models used are described in [Fall98]. The movements scenario files used in each simulation are characterized by pause times; we studied 6 different pause times using 10 different simulations for each pause time with a maximum nodes' speed of 20 m/s. A pause time of 0 represents a network of very high mobility in which all nodes move continuously, and a pause time, equal to the simulation time represents a stationary network. The traffic sources used are constant bit rate (CBR) traffic. Each traffic source originates 512 bytes data packets, with rate 4 packets/second. Maximum number of CBR sources used is (3, 13, 25, 38, 50) corresponding respectively to network sizes of (20, 25, 50, 75, 100 nodes).

4.4.2 Evaluating the Performance of EC-DSR Versus DSR: Small Size Network

In this evaluation, we analyze the behavior of EC-DSR under a range of various mobility scenarios. Our simulations have been run using a MANET composed of 20 nodes moving over a rectangular 1200 m x 300 m space, and operating over 600 seconds of simulation time. Nodes in our simulation move according to the RWP mobility model [Bet02]. The movement scenario files used in each simulation are characterized by pause times; we studied 6 different pause times: 0, 30, 60, 120, 300, and 600. We studied the following main performance metrics in our evaluation: average end-to-end delay, delivery ratio, dropped packets, control packets overhead, and control bytes overhead. Our obtained results and analysis are illustrated below.

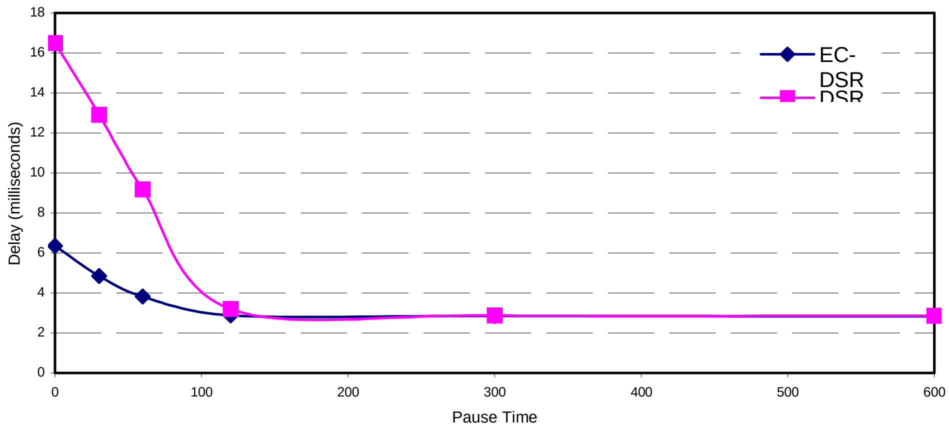


Figure 4.3 Average end-to-end delay

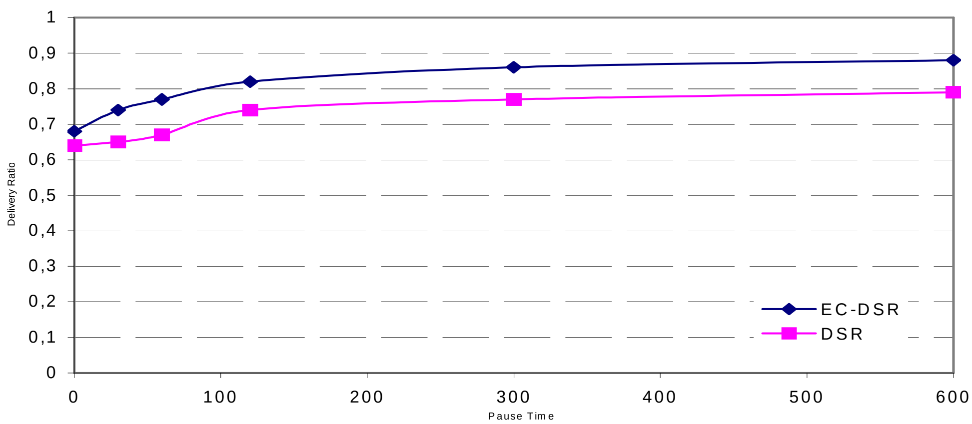


Figure 4.4 Average delivery ratio

Figure 4.3, shows the average end-to-end delay as a function of the mobility scenario. In this figure, results for the protocol EC-DSR are compared with those of DSR. This delay is calculated only for the data packets that have been successfully received. We can see that the delay has nearly the same behavior for both protocols at intermediate and low mobility. At high mobility, DSR causes an increase in delay over EC-DSR thanks to the nodes' selection mechanism applied in EC-DSR. In fact, using the selection mechanism of EC-DSR minimizes the broadcast scope and constructs more minimum hops stable paths with longer route lifetime consuming less energy, thus achieving better impact on the delay. When the network becomes stable, the delay difference is reduced. In this case the two protocols show nearly the same behavior since routes become stable.

Results comparison for the delivery ratio is depicted in Figure 4.4. Delivery ratio is determined by the ratio of the number of data packets actually delivered to the destination versus the number of data packets supposed to be received. This number presents the effectiveness of the protocol. We can see that the two protocols point up the same behavior in all mobility cases. EC-DSR outperforms DSR showing incremental delivery ratio for all mobility cases; this refers to its rigid long-lived routes by means of selecting stable high-energy paths. The obtained result confirms the expected behavior of EC-DSR, which tends to choose links' quality paths reacting better towards frequent distortion and interference.

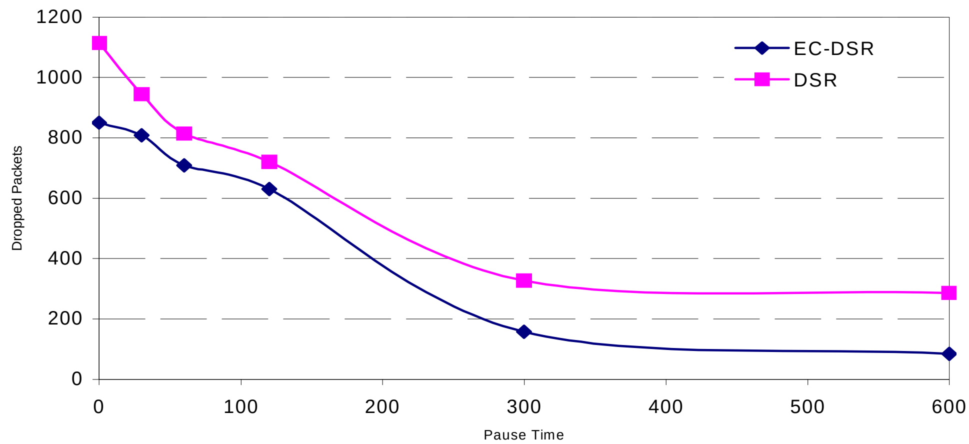


Figure.4.5 Average packets drops

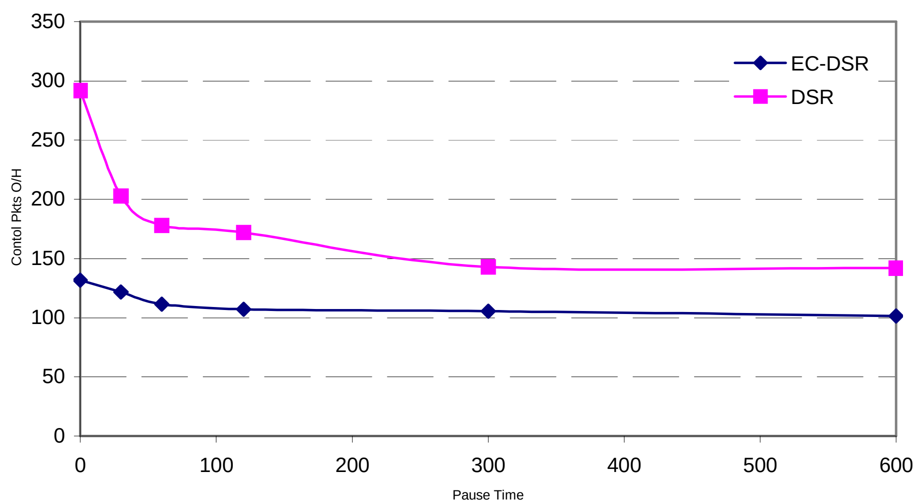


Figure 4.6 Packets Control Overhead

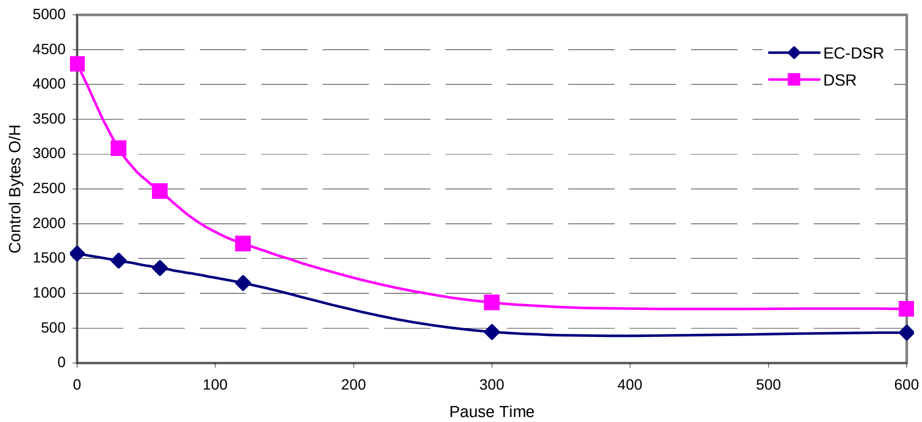


Figure 4.7 Bytes Control Overhead

Figure 4.5 shows the effect of EC-DSR and DSR on the number of dropped packets. EC-DSR has a weaker impact on packets drop for all mobility cases, while DSR has more impact on packets drops in these cases. When link failure occurs, queue congestion is increased in DSR causing more packets drops. In contrast, EC-DSR avoids frequent link failures. We explain this by the fact that the route lifetime of EC-DSR paths is longer, at the same time, the stability features allows EC-DSR to outperform DSR.

The control overhead comparison is subsequently illustrated in Figure 4.6 and 4.7. We observe a significant difference between EC-DSR and DSR in terms of control packets generated during simulation for all cases of mobility. EC-DSR shows less control overhead providing better results in terms of both packets and bytes overhead. The effective node selection mechanism in EC-DSR causes packets generation only to certain nodes, and the fact of selecting high-energy paths decreases the probability of link failure and the need to send more routing packets to recover this failure. On the contrary, DSR relies on broadcast flooding in its route discovery process. EC-DSR outperforms DSR in bytes overhead as the source route accumulation takes place for the selected nodes only, thus saving lot of bytes caused by source route headers. On the contrary, DSR accumulates the source route during route request broadcast, thus consuming more overhead bytes.

4.4.3 Evaluating the Performance of EC-DSR versus DSR: Large Size Network

In our analysis, we simulated nodes movements over rectangular 1200m x 500m topography, operating over 1500 seconds of simulation time. Nodes' movement follows the RWP mobility model [Bet02]. We analyze the performance of EC-DSR versus DSR using the absolute difference, which we define as (*DSR performance metric value – EC-DSR performance metric value*). Several performance metrics are used in our performance evaluation and comparison, which are: (1) *delivery ratio* in terms of the number of packets correctly received with respect to the total number of packets sent, (2) *forwarding delivery* in terms of the ratio of the number of nodes forwarding packets correctly to the number of transmitted packets, (3) *forwarding control packets overhead* in terms of the total number of the control packets forwarded in the network, and finally (4) *end-to-end delay*.

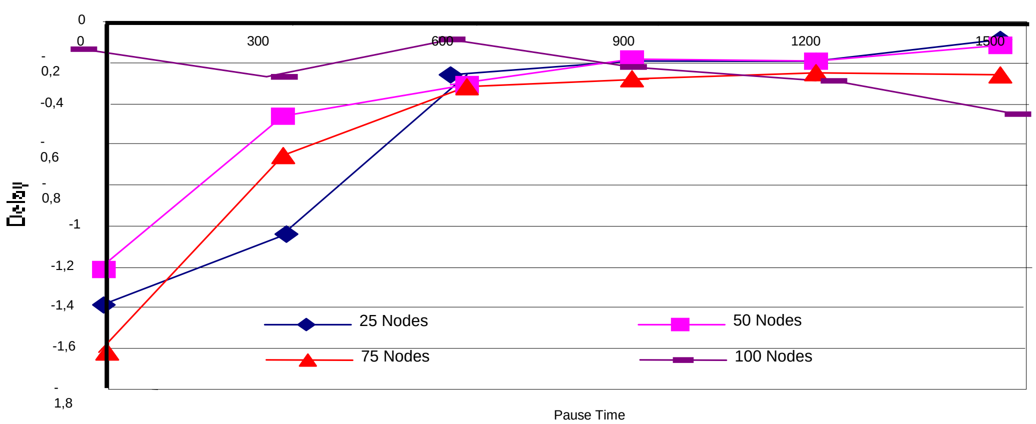


Figure 4.8 EC-DSR Vs DSR Absolute Delay

Figure 4.8, shows the absolute delay. For network topologies 25 to 75 nodes, DSR has weaker impact on the delay compared to EC-DSR. The delay difference increases with mobility. In 100 nodes topology, EC-DSR has weaker impact on the delay compared to DSR for nearly all mobility cases. Although EC-DSR allows the selection of longer routes that may consume more delay, in 100 nodes case the DSR criteria in routes selection invokes more probability of link failures that introduces more delay during the re-transmission and maintenance.

The absolute forwarding control overhead is illustrated in Figure 4.9. At all mobility cases and all topologies, DSR exerts higher overhead compared to EC-DSR. This is due to the fact that EC-DSR minimizes the flooding scope during route discovery. On the other hand, DSR necessitates the transmission of more control packets.

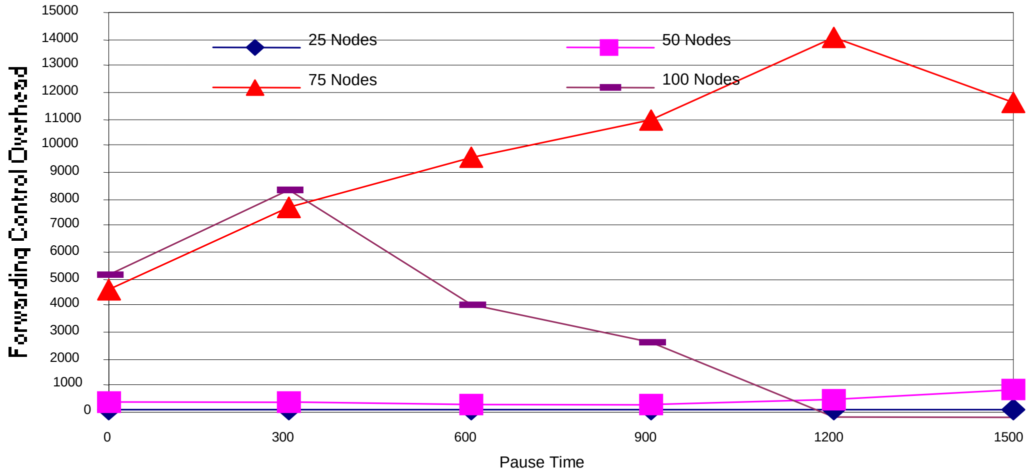


Figure 4.9 EC-DSR versus DSR Absolute Control O/H

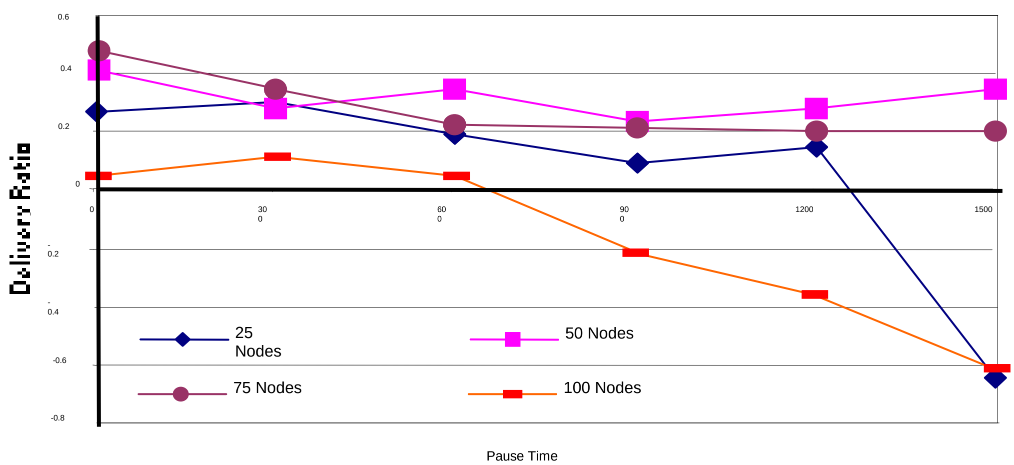


Figure 4.10 EC-DSR versus DSR Absolute Delivery Ratio

In Figure 4.10, DSR outperforms EC-DSR in terms of delivery ratio at different mobility's for network topology 25 to 75 nodes. As mentioned previously, EC-DSR exerts more delay due to applying certain selection criteria during route discovery, introducing more delay. This translates the superiority of DSR in terms of delivery ratio. In general, the delivery ratio implies the end-to-end connection between each two nodes. For EC-DSR, the packets may traverse more forwarding nodes, as it does not invoke the shortest path criteria, consuming more delay despite its improvement in selecting more stable energy efficient routes. We see that EC-DSR becomes more efficient when the topology becomes more complex (100 nodes) and mobility is lower. In this case, the overhead of EC-DSR mechanisms has less effect on its efficiency compared to the economic energy consumption factor that allows the choice of more stable paths showing better behavior.

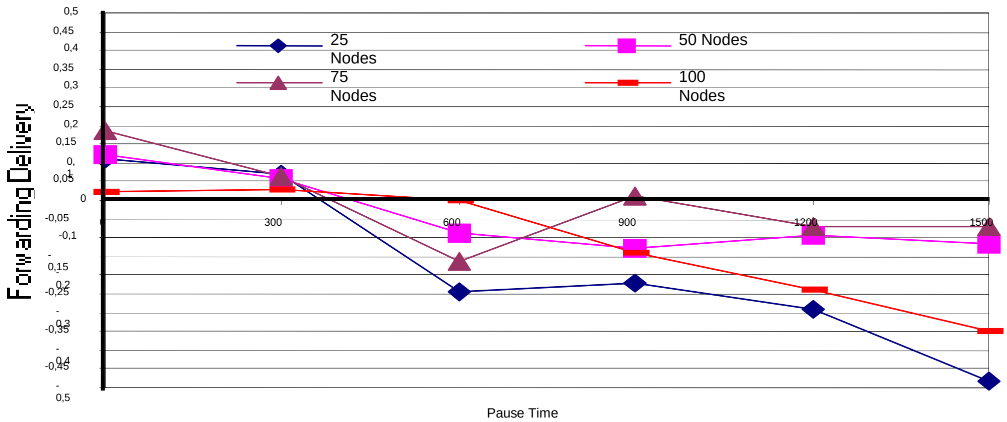


Figure 4.11 EC-DSR Vs DSR Absolute Forwarding Delivery

At higher mobility cases, DSR outperforms EC-DSR in its forwarding delivery for all topology cases, as shown in Figure 4.11. Due to the complex route selection process in EC-DSR, it is less efficient in repairing routes in highly dynamic networks cases, which translates this behavior. For less dynamic networks, EC-DSR outperforms DSR at all topology cases. As explained previously, the efficiency of EC-DSR protocol weakens the shortcoming of its mechanisms complexity leading to this improvement.

4.4.4 Mobility Models Impact on EC-DSR Performance

In this section, we evaluate EC-DSR performance using different mobility models, showing the impact of choosing the mobility model on the protocol's performance [Mou05]. Nodes in our simulation move according to the RWP [Bet02], RPGM [Hon99], and PM [Cam02] models. They move over square 670m x 670m topography, operating over 900 seconds of simulation time. The mobility scenarios for RWP model are generated under ns2, while those for RPGM and PM models are generated using Bonn-Motion tool [ics]. For RPGM mobility scenarios, we have chosen the maximum group size (in terms of number of nodes) to be 10 for 50 nodes network topology and to be 20 for 100 nodes network topology.

Several performance metrics are used, which are: (1) *delivery ratio*, (2) *end-to-end delay*, (3) *control overhead* in terms of the total number of control packets transmitted by the protocol during the whole simulation, (4) *link failure* in terms of the number of link breaks during data transmission, and (5) *energy consumpotion*, in terms of the nodes average energy level, measured at the end of the simulation, as a percent of their initial energy (see Equation 4.6).

$$E = \sum_{i=1 \rightarrow N} (E_L / N) \tag{4.6}$$

$E_L = (E_{Initial} - E_{Current}) / E_{Initial}$

N : Number of nodes

$E_{Initial}$: Initial energy for each node at the beginning of the simulation

$E_{Current}$: Consumed energy for each node until the current time

Figure 4.12 illustrates the obtained delivery ratio. In general, EC-DSR delivery ratio increases when mobility decreases, attaining its highest value at stationary network. Superlative delivery ratio is provided with the PM model for 50 nodes network. In fact, this behavior is due to the movements of all nodes together tracking the leader node. During these movements, velocities do not change abruptly and the randomness in motion is restricted. Thus, the probability of finding long-lived routes tends to become high. It is also noticed that the impact of RPGM model on the delivery ratio outperforms that of RWP model for 50 and 100 nodes networks. This behavior is quite normal, as RPGM model promotes nodes' movements in groups. This permits RPGM groups' constitution of sources and their corresponding destinations, either within the same group or within neighbor groups. Hence, allowing more successful data packets reception.

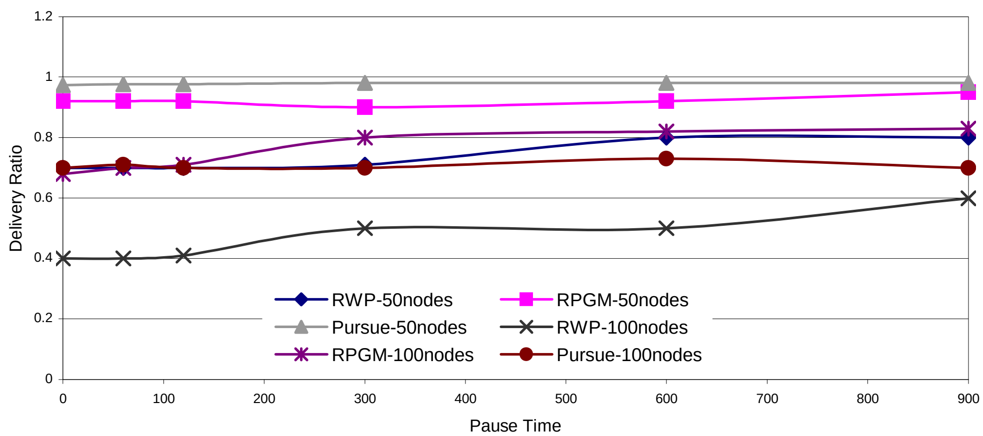


Figure 4.12 EC-DSR Average Delivery Ratio

In 100-node networks, RPGM shows a superior impact on the delivery ratio. Its delivery ratio in this case outperforms that of 50 nodes network using RWP model, showing the strapping scalability of RPGM model. Furthermore, at intermediate and low mobility, its delivery ratio surpasses that of PM. Actually, PM provides more stable routes in this case implying more load on these route and affecting its delivery ratio.

The average end-to-end delay for data transmission is shown in Figure 4.13. Although RWP shows delay decrease with mobility decrease, it has the worst impact on the delay for 50 and 100-node networks. This comes as a result of the continuously unpredicted random motion of each node, allowing more link breaks and badly affecting the delay especially at high mobility cases. At low mobility RWP effect on the delay nearly outperforms that of RPGM. RPGM behavior is due to the fact of unfair traffic distribution at low mobility cases, since most nodes of each RPGM group share nearly same paths due to higher paths stability at this case. Otherwise, RPGM shows delay decrease for 100-node networks at intermediate and low mobility cases, due to the higher probability of finding more stable routes in the nodes' caches at intermediate and low mobility cases; which saves time to discover new routes and reduces the delay. A nearly constant delay is provided for 50-node networks, as the number of nodes per RPGM-group is nearly appropriate for the intermediate network size, thus allowing fair traffic distribution among all nodes of all groups.

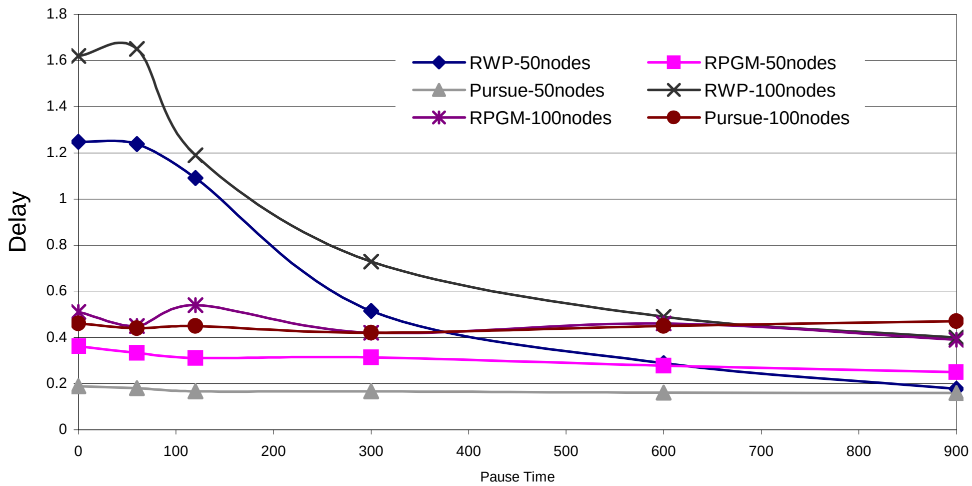


Figure 4.13 EC-DSR Average Delay

Two features are noticed for PM model. Firstly, the resulting delay is nearly constant for all networks' size. In addition, it outperforms the delay resulting from using RWP (for all networks' size) and RPGM (for 50-node networks). The former is due to the nodes same movement's behavior for all mobility cases and the latter is due to minimizing the randomness scope in nodes' movements and guaranteeing nearly constant velocity for all nodes. These facts allow a behavior in favor of PM model. However, RPGM delay impact is slightly improved compared to that of PM at high mobility cases for 100-node networks. Since the network size is large and the nodes are highly active, traffic distribution on groups with different movements is preferable to avoid congestion of nodes when shared paths are frequently re-constructed with PM case.

Figure 4.14 shows EC-DSR control packets overhead using the three mobility models. We notice that RPGM model always exhibits fewer overhead compared to RWP model. This is due to the fact that RPGM model does not frequently employ pause time during its motion pattern, and the nodes' movements are not completely random. This feature allows the source to localize the receiver(s) faster. It allows also each receiver to construct its route towards the corresponding source rapidly, implying less control overhead needed from both sides.

Regarding the PM model, it shows nearly the same impact as RPGM on the control overhead for low mobility cases for 50 nodes network. At high and intermediate mobility, PM model has the minimum impact on the control overhead compared to RWP and RPGM models. This is due to its rapid route discovery, compared to RWP and RPGM, in active network cases due to the nodes' similar behavior in their movements, thus giving a lesser impact to the PM model on the control overhead at these cases. On the other hand, RPGM impact on the control overhead is improved compared to that of PM model for 100-node networks. RPGM allows more existence possibility for receiver(s) and their corresponding source(s) within the same group or in neighbor groups, which minimizes the control messages. But PM allows all nodes to follow a certain leader, increasing the localization range sometimes to the whole size of the network.

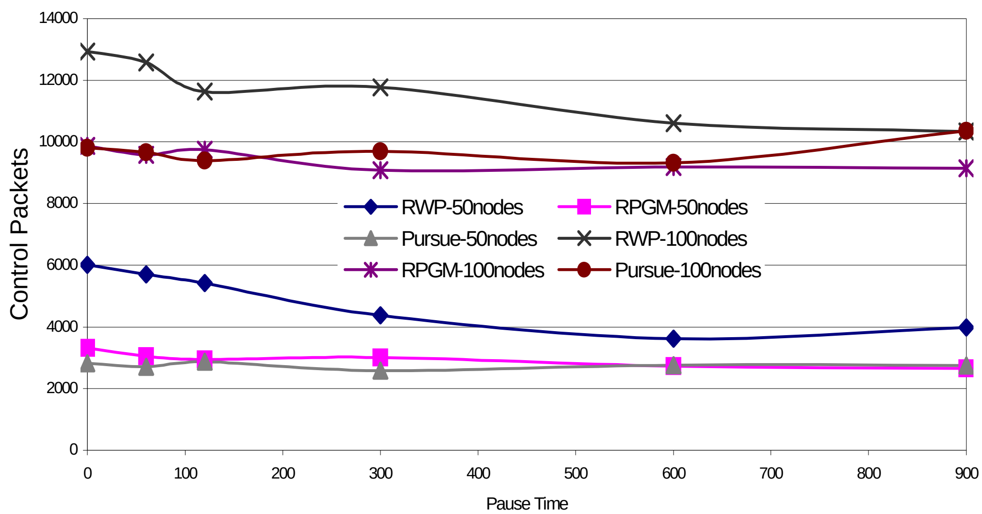


Figure 4.14 EC-DSR Average Control Overhead

The behavior of EC-DSR in terms of link failure is shown in Figure 4.15. We calculate the average link failure to illustrate the protocol's robustness at different mobility types and with different mobility models. An obvious feature at the case of 50 nodes network is that, RWP and RPGM models depict nearly the same general behavior, where they show their maximum link failure rate at intermediate mobility. Actually, at intermediate mobility the network is less dynamic permitting more stored routes in the source nodes' caches towards the destination nodes. Thus the route discovery frequency is lower than highly active network case. Also it takes more time for all the stored routes to be deleted from the source nodes' caches, exposing the network to more link failures resulting from the trial and usage of all the stored routes. In spite of this peak behavior, RPGM model performs much better at intermediate mobility compared to RWP model.

Firstly, RPGM peak interval at this case is much shorter compared to RWP peak interval. Secondly, its impact on link failure during this peak interval is 60% lower than RWP model impact. Still, for 100-node networks, their impact on the link failure decreases with mobility decrease due to the possibility of finding more stable routes in this large network, thus the traffic is better distributed. Comparing the behavior of all the mobility models, RPGM model shows lower link failure rate than RWP. This comes as a result of higher probability for RPGM groups to have more than one destination for the same traffic source or for different traffic sources. In addition, there is a possibility for the destinations to traffic source(s) to be in near groups. This allows the existence of common stable paths/sub-paths leading to the receivers. On the other hand, PM model exhibits the minimum impact on link failure rate for all networks' size. Moreover, it shows nearly constant behavior with different types of mobility, due to the highest probability of finding long-lived routes. This feature makes the PM model very efficient in high scalable network cases.

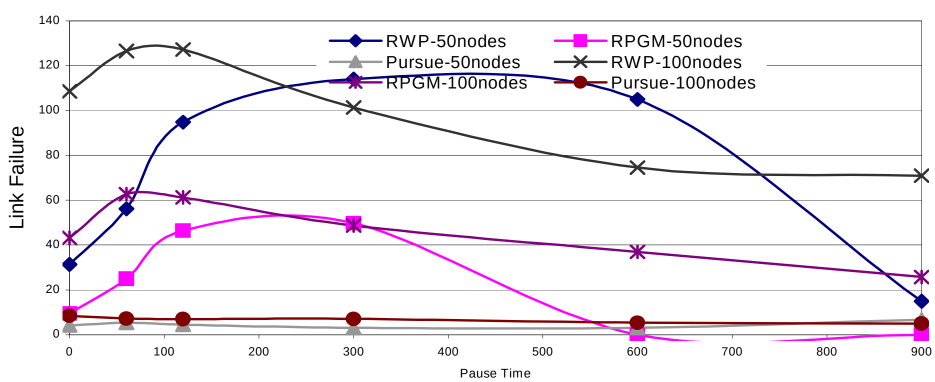


Figure 4.15 EC-DSR Average Link Failure Rate

Figure 4.16, shows EC-DSR efficiency in energy consumption when using the three mobility models. In our evaluation, we used the average energy level for all nodes as our metric. It is calculated at the end of the simulation, showing the amount of battery consumed during the simulation. We measure it as a percent of the initial battery energy assuming that all nodes start with the same initial energy.

A unique feature of EC-DSR appears at its energy consumption, where it shows less energy consumption (higher energy level) at high mobility cases for all networks' size. At high mobility cases, new routes are frequently discovered and constructed due to the rapid random change of nodes' movements. Actually, they use the more stable and higher energy level paths in their construction, allowing more recent stable routes to always exist at the route cache of each traffic source. By this, better traffic distribution is allowed and paths overloading is reduced minimizing the paths' energy consumption. At intermediate mobility, energy level is nearly better compared to low mobility showing lower consumption for 50-node networks and vice-versa for 100-node networks. In fact, at intermediate mobility, the probability for stable paths becomes higher allowing better traffic distribution and lower energy consumption for the medium size network. Regarding large size network, low mobility achieves a better energy consumption compared to intermediate mobility. In this case, stable network is recommended to assure better traffic distribution on the large number of paths at this scalable network.

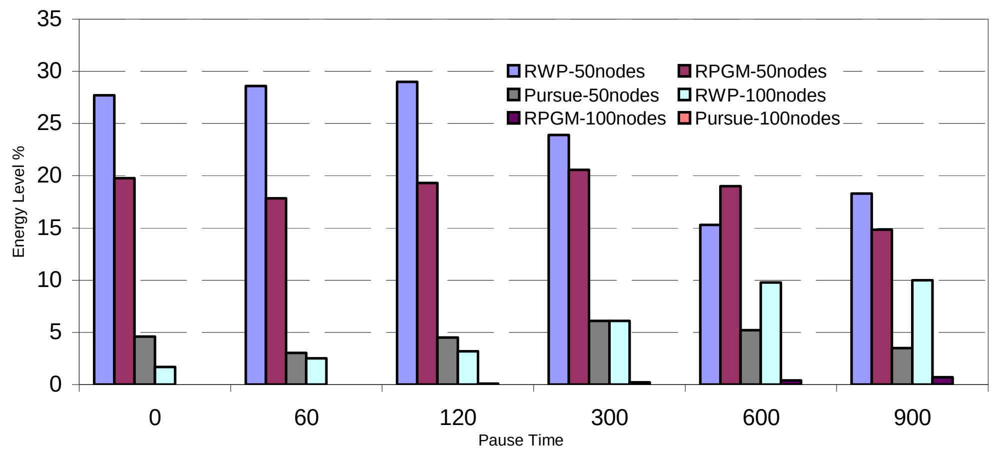


Figure 4.16 EC-DSR Average Energy Level

In conclusion, RWP model exhibits less energy consumption at different mobility types and different networks' size. At 50-node networks, the RWP model consumption is from 3 to 5 times lower than PM model consumption and from 1.2 to 1.5 times lower than the consumption of RPGM model. At 100-node networks, the RWP model consumption is from 3 to 10 times lower than PM model consumption and from 3 to 5 times lower than the consumption of RPGM model. It is also noticed that for 100-node networks, nodes' energy is totally exhausted for the PM (energy level = 0) at all types of mobility, and for RPGM at highly active networks. The fact that PM model exhibits the highest energy consumption is due to the longevity of the constructed routes, as well as the existence of a great possibility for larger number of nodes to be reached via the same paths/sub-paths, as a result of nodes movements in a group behavior. Thus, more charge is added to the nodes constituting these routes implying more energy consumption. On the other hand, there is a possibility of larger number of nodes to be reached via the same paths/sub-paths in case of RPGM model, thus causing more energy to be consumed at these commonly used paths.

Figure 4.17, 4.18, and 4.19 illustrate the effect of energy consumption on the link failure rate for medium and large network sizes and with different mobility models. It is clearly shown that, at all mobility models and all network sizes, there exists an inversely proportion relation between the energy level and the link failure, hence reinforcing the objective of our energy conserving mechanism to achieve improved performance in such type of dynamic networks.

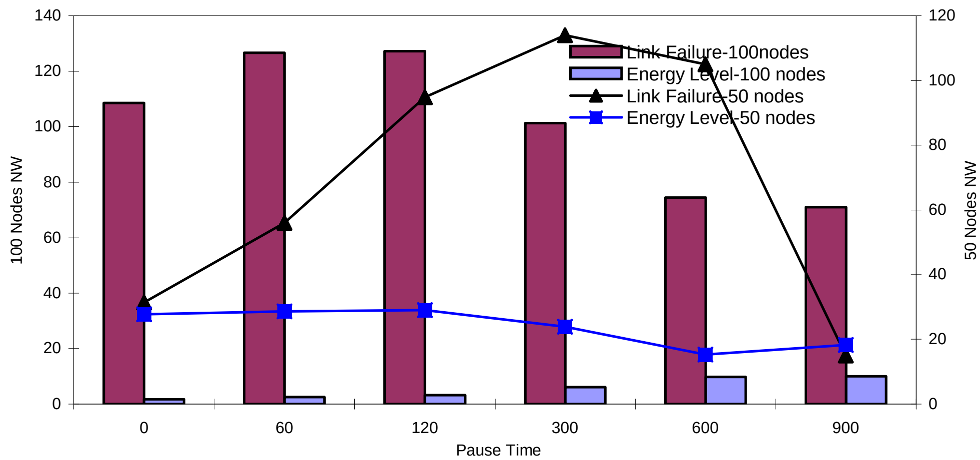


Figure 4.17 RWP Energy Level Vs Link Failure

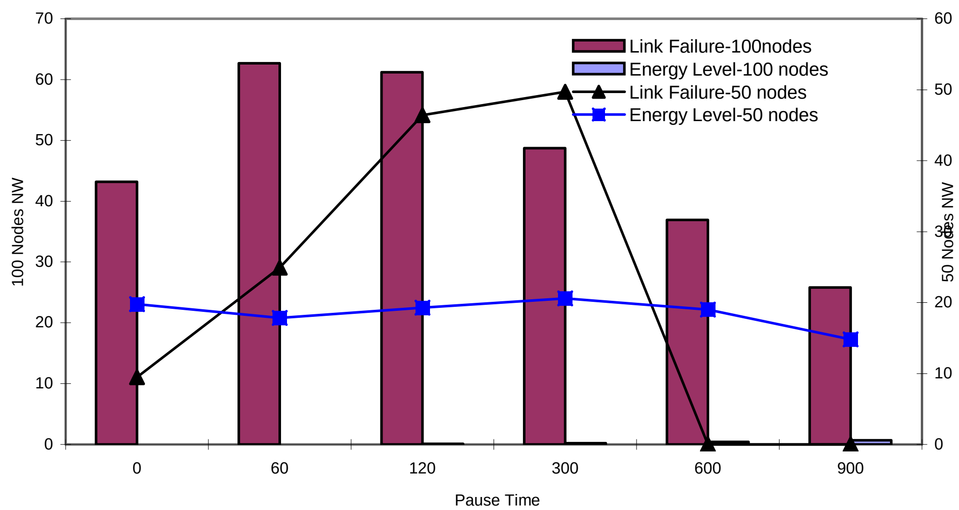


Figure 4.18 RPGM Energy Level Vs Link Failure

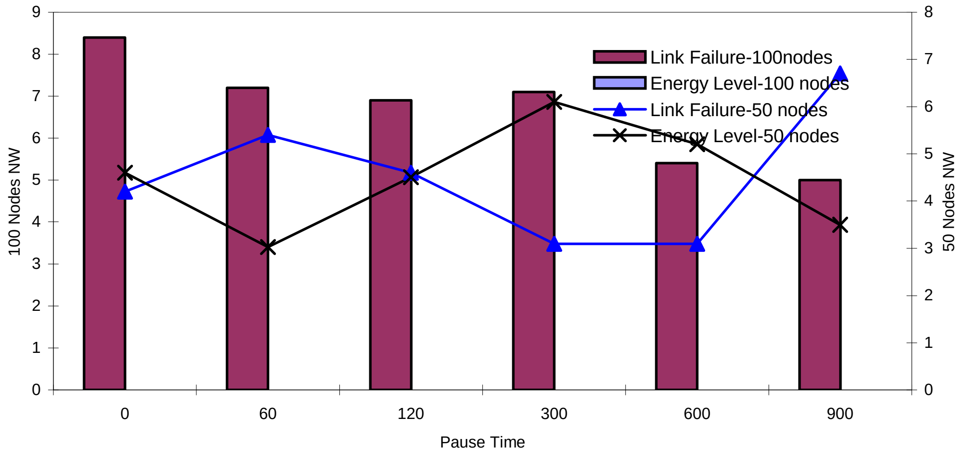


Figure 4.19 PM Energy Level Vs Link Failure

4.5 Summary and Conclusion

In this chapter, we are concerned with energy efficient routing in MANETs. We started by a review on the related work, stating the motivation to our contribution in this subject. Then we presented our proposed EC-DSR protocol and evaluated its performance versus DSR.

Throughout our study, we could conclude that the route breakage (failure), which occurs frequently in ad hoc networks due to the nodes mobility, wastes battery power and thus causes a decrease in the lifetime of the wireless nodes. Moreover, the flooding of the route request and route reply packets in the on-demand routing protocols may result in considerable energy drains. Nevertheless, the periodic updates in table-driven routing protocols negatively influence the energy conservation.

Considering all these facts, we presented an approach that enhances the unicast routing performance via integrating ad hoc related characteristics. Our proposition investigated the routing problem in MANETs through considering a distinctive approach exploiting the quality of the connectivity. We addressed the energy conserving issue in conjunction with paths' availability and nodes' strong connectivity in order to provide robustness to host mobility and adaptability to wireless channel fluctuations. Our scheme is based on the source routing approach, and is named Energy Conserving Dynamic Source Routing (EC-DSR).

EC-DSR aims at reducing the broadcasting scope in the route discovery process, which attempts to minimize the message overhead of computing routes. In addition, some selected routes are only constructed. The chief benefit of these selected routes is their efficient energy consumption. Moreover, there would be a little need to modify them frequently, hence decreasing the overhead in the maintenance phase and improving delay.

We carried out a full performance evaluation and analysis of EC-DSR protocol. Our simulation results for small size network show a significant reduction in the routing overhead while the packet delivery ratio is enormously increased and the delay is not greatly affected. In addition, the amount of dropped packets is low indicating the robustness of EC-DSR against mobility in such type of networks.

Our performance evaluation for large size network demonstrates that EC-DSR is more efficient compared to DSR at more traffic loads when the number of connections between nodes increases. We also use RWP, RPGM, and PM mobility models in our performance evaluation as a mean of studying the effect of changing the mobility model on the protocol's performance. It is concluded that our protocol becomes more efficient in the case of using PM and RPGM models due to the grouped movement behavior for all nodes, which is useful and efficient in the case of networks with large number of nodes. Furthermore, PM shows an exclusive behavior: it provides superlative delivery ratio, delay, and link failure at different mobility types. Whereas, it does not compete for energy consumption compared to RWP and RPGM mobility models. This is due to the more stable constructed mesh with the PM model, which concentrates consumption on nearly the same nodes. From our previous observation and study, it is clear that PM and RPGM models show superior behavior. Thus we conclude that EC-DSR is more robust and efficient in grouped movement cases for highly scalable ad hoc networks.

In the next chapter we propose SRMP, a novel multicast routing protocol in ad hoc networks. SRMP is an on-demand mesh-based protocol that provides connectivity quality while conserving the energy consumption.

CHAPTER 5 SOURCE ROUTING-BASED MULTICAST PROTOCOL (SRMP)

In this chapter, we focus on one critical issue in mobile ad hoc networks that is multicast routing. We apply a different type of routing strategy to provide efficient multicast routing. We also modify the conventional tree structure and deploy a different reliable topology that guarantees the connectivity quality between group members. Consequently, we proposed a new multicast routing protocol, named Source Routing-based Multicast protocol (SRMP). Throughout this chapter, we provide a detailed description of our protocol in Section 5.2, showing its operation in Section 5.3. We evaluate its performance under different network configurations, mobility types, and mobility patterns in Section 5.6. We also compare its performance with ADMR and ODMRP multicast protocols.

5.1 Background and Motivation

Most existing multicast protocols face several problems in tree maintenance and frequent reconfiguration when link failures occur. These protocols often depend on upstream and downstream nodes requiring storage and control overhead. While some protocols consider the shortest path as a criterion for path selection, it is not usually suitable to the high and unpredictable variation of the topology of ad hoc networks.

We propose a new on-demand multicast routing protocol, named **Source Routing-based Multicast Protocol** (*SRMP*). This protocol operates in a loop free manner and attempts to minimize both routing and storage overhead in order to efficiently provide robustness to host mobility, adaptability to wireless channel fluctuations, and optimization of network resources use. SRMP applies the source routing mechanism, from which the name is inspired, defined in the Dynamic Source Routing (DSR) protocol [Joh96] to avoid channel overhead and to improve scalability.

Our proposition mainly addresses the concept of the connectivity quality. This takes place through considering two important issues in solving the multicast routing problem:

(i) path availability concept, and (ii) higher battery life concept. The former allows the protocol to distinguish between available and unavailable paths. We define the path as available or unavailable according to the radio quality of each link constituting the path and the nodes stability at both ends of each link. The latter biases the protocol towards choosing a channel that tends to power conserving. The combination of these two issues allows the selection of available and power conserving links that offer a quality of connectivity.

In the following sections, we give a detailed explanation of SRMP, describing its operation and data structures. Then, we present a full performance evaluation for this protocol comparing it to ADMR and ODMRP, considering various network configurations, traffic scenarios, mobility patterns and multicast groups composition.

5.2 Protocol Overview

SRMP is an on-demand multicast routing protocol. A mesh structure (arbitrary sub network) is established on-demand to connect each multicast group members, thus a richer connectivity is provided among multicast group(s) members.

We obtain several advantages over tree-based protocols:

- Redundant paths between members are provided: thus the multicast topology grants robustness and richer connectivity between group members;
- The drawbacks of multicast trees are avoided: intermittent connectivity, traffic concentration, frequent tree reconfiguration, non-shortest path in a shared tree;
- Efficient criteria in selecting nodes are applied: where paths' availability and nodes' strong connectivity are fulfilled.

To establish a mesh for each multicast group, SRMP uses the concept of forwarding group (FG) nodes. We consider the forwarding group as a set of selected nodes responsible for forwarding multicast data between any member pairs [Chi98]. This scheme can be viewed as a "limited scope" flooding within a properly selected forwarding set. The key challenge in efficient multicasting is the choice of FG nodes and how to elect and maintain them. SRMP achieves a compromise between the size of the selected nodes, and the availability and stability of the selected paths. During the mesh construction, we apply the source routing mechanism proposed in DSR unicast protocol, in a modified manner.

5.2.1 FG selection criteria

We invoke efficient FG nodes selection criteria; these criteria allow the establishment of a robust mesh structure granting a quality of connectivity:

- Available paths based on future prediction for links' state: by "a path being available", we mean that the radio quality of each link in the path satisfies the minimal requirements for a successful communication;
- Reliable paths: where nodes are stable with respect to their neighbors;
- Strong connectivity between nodes: where each pair of neighbors is highly associated;
- Higher battery life: through selecting nodes that exert lower power consumption.

To achieve this, we define four metrics as our selection metrics for paths selection during the mesh establishment: association stability, link signal strength, link availability, and battery life. This mixed metric approach can be used as a best indicator in paths selection. However, the problem is that finding a path subject to multiple constraints is inherently hard, and sometimes can be NP-complete problem [Zhe96]. Consequently, we undertake, in Chapter 6, an adaptive study for the thresholds used on our metrics during the selection phase.

5.2.1.1 Association stability

This metric measures how long each pair of neighbor nodes is stable with respect to each other. It has been first introduced in ABR protocol [Toh97], and is known as the degree of association stability. In our protocol, association stability is calculated by each node with respect to each neighbor through the use of *associativity ticks* field stored in the node's *Neighbor_Stability_Table*. This field is incremented each time the node receives a beacon indicating a neighbor's existence. A node is considered stable with respect to a certain neighbor when the accumulated *associativity ticks* value corresponding to this neighbor fulfills a certain predefined threshold named the *association_stability_threshold*.

When a node receives no more beacons from a certain neighbor up to a predefined period of time, the node sets its *associativity ticks* field corresponding to this neighbor to zero. This takes place when either the node or its neighbor moves from each other range. Otherwise, the degree of stability takes various levels (low, intermediate, high) according to the corresponding value of the *associativity ticks*.

5.2.1.2 Link signal strength

This metric measures the signal strength between each node and each of its neighbors indicating the strength of connectivity at each link connecting a pair of neighbors. SRMP uses this metric to select links that offer stronger connectivity between nodes. The link signal strength is calculated according to the level of strength the neighbor beacon is received at each node, where it is stored in a *signal strength* field in the node's *Neighbor_Stability_Table*, and classified as weak or strong. In fact, the classification is done through comparing the level of strength of the received beacon with a certain predefined threshold named the *signal_strength_threshold*.

Similar to the association stability, when no more beacons are received by a node from a certain neighbor up to a predefined period of time, the node sets its corresponding *signal strength* field to null, indicating either node or neighbor movement.

5.2.1.3 Battery life

This metric periodically calculates the energy level at each node in terms of its current battery power. Actually, the energy level at each node is a decreasing function of time and processed packets. We introduce this metric for power conservation during our routing process, such that paths with higher battery life, indicating less power consumption, are only selected. Higher battery life is decided according to a certain predefined threshold named the *energy_level_threshold*.

Each node is considered as possessing high battery life, as long as its current *battery life* counter, $\mathbf{B_p(t)}$, fulfills the predefined threshold. Equation 5.1 shows how $\mathbf{B_p(t)}$ value is calculated, where we consider $\mathbf{B_p(0)}$ as the initial battery power predefined for each node and has a constant values for all nodes.

$$B_p(t) = B_p(\text{current}) - [PC_{gp} + PC_{rp} + PC_{fp} + K] \qquad (5.1)$$

$\mathbf{B_p(t)}$: Battery power at time t, - B_p(current) : Current battery power (Initially, B_p(current) = $B_p(0)$)
$\mathbf{PC_{gp}}$: Total power consumed for each generated packet (including processing and transmission)
$\mathbf{PC_{rp}}$: Total power consumed for each received packet (including reception and processing)
$\mathbf{PC_{fp}}$: Total power consumed for each forwarded packet (including reception, processing and transmission)
K: Power consumed by the node itself (equipment)

$\mathbf{B_p(t)}$ is calculated periodically by each node, where its value is stored in a certain field reserved for each node named *battery life* field.

5.2.1.4 Link availability estimation

Path reliability is an important consideration to eliminate rerouting operation and select an optimal path. SRMP decreases the possibility of unreliable paths construction, through the use of link availability estimation metric during the FG nodes selection for the construction of its different paths. This metric is based on a probabilistic model for future availability of the path. We use prediction-based link availability estimation, described in [Mou01], to estimate the future availability of each link in the path.

The basic idea of this estimation is to firstly let a node predicts a continuous time period $\mathbf{T_p}$ that a currently available link will last from time $\mathbf{t_0}$ by assuming that both nodes of the link are keeping their current movements (i.e. speed and direction) unchanged. Then the probability **L(T_p)** that the link will last to **t_0+T_p** is estimated by considering possible changes in the nodes' movements occurring between **t_0** and **t_0+T_p**.

We calculate this probability at each node towards each of its neighbors, following the probabilistic model introduced in [Jia01]. This model assumes mobility epochs for nodes' movements, where an epoch is a random length interval during which a node moves in a constant direction and speed. The link availability can be predicted making use of Equation 5.2, such that higher probability of link availability is decided according to a certain predefined threshold named the *link_availability_threshold*.

$$\mathbf{L(T_P)} \approx \frac{1-e^{-2\lambda T_P}}{2\lambda T_P} + \frac{\lambda T_P * e^{-2\lambda T_P}}{2} \qquad (5.2)$$

T_P: the predicted interval of time at which the link will be active for (t_0 + T_P) given that it is active during the time period t_0.
λ^{-1}: is the mean of the exponentially distributed mobility epoch.

The calculated **L(T_P)** value is stored in a *link availability* field in the node's *Neighbor_Stability_Table*, this field is periodically updated by each node and indicates the degree of link availability with respect to each neighbor. A link is considered as available between a node and its neighbor, when the *link availability* value corresponding to that neighbor fulfills a certain predefined threshold named the *link_availability_threshold*.

5.2.2 Data Structures

We define four data structures to enable SRMP routing. Network nodes running SRMP are required to maintain these data structures.

Neighbor_Stability_Table: it gathers continuous node-neighbor information. An entry is created for each neighbor, storing stability information between the node and this neighbor. Stability information includes node-neighbor stability in terms of degree of association stability, connectivity strength in terms of signal strength, and link availability of this node with each neighbor. Table 5.1, illustrates this table, where the *Type* field is used to indicate if the concerned neighbor is a member or non-member of the group.

Table 5.1 SRMP Neighbor_ Stability_Table

Neighbor	Type	Associativity Ticks	Signal Strength	Link Availability

Multicast_Message_Duplication_Table: identifies each received *Join-request* or data packet and is used to detect duplication in these packets reception. To identify the message, the *source ID* of each newly received message is stored in this table together with its sequence number. By the time the node receives another messages, it checks its table entries for an identification that resembles the received message and discards this message if duplication is discovered. The message type is also stored to differentiate between a *Join_request* and a data packet. Table 5.2, illustrates this table, where FIFO or LRU scheme might be used to expire old entries.

Table 5.2 SRMP Multicast _Message_ Duplication_Table

Source ID	Sequence Number	Type

Multicast_Routing_Cache: stores all the possible routes between each node and the different multicast group(s) receivers, such that the node is a mesh member of the corresponding multicast group. An entry for a multicast group is first created during the first *Join_reply* received by a node from a multicast receiver, and other entries are created by the reception of other *Join-replies*. Entries are refreshed to the same multicast receiver during the propagation of data packets through the node. A timer field is used in each entry to indicate route validation, where it stores the last time a route was stored or refreshed. Table 5.3, illustrates this table.

Table 5.3 SRMP_Multicast _Routing _Cache

Group ID	Type	Route to receiver	Timer

Receiver_Multicast_Routing_Table: maintained at each receiver for each multicast group, stores the created route between the receiver and each multicast source. Entries for each source are created by the first data packet reception from the corresponding source. A timer field is used to refresh the table entries with continuous data packets reception, thus indicating route validation. Table 5.4, illustrates this table.

Table 5.4 SRMP_Receiver_ Multicast_ Routing_ Table

Group ID	Source ID	Route to source	Timer

5.3 SRMP Operation

Similar to the operation of on-demand routing protocols, the protocol consists of a request phase and a reply phase. The request phase invokes a route discovery process to find routes to reach the multicast group. Different routes to the multicast group are setup during the reply phase through the FG nodes selection and mesh construction.

The following sections describe the request phase, reply phase, FG nodes selection, and data transmission and forwarding through the constructed mesh.

5.3.1 Route Request Phase

This section discusses the route request phase of our protocol. It starts when a source node, which is not a group member, wishes to join the group. At this time, it broadcasts a *Join-request* packet to its neighbors invoking a route discovery procedure towards the multicast group. The *Join-request* packet is shown in Figure 5.1, it contains the ID of the source node in its *Source ID* field, the multicast group ID in its *Destination ID* field, and a *Sequence number* field. The S*equence number* is set by the source node for each generated *Join-request* packet, and is used to detect packet duplication. To eliminate the possibility of receiving multiple copies of *Join-request* packets, each node receiving a *Join-request* packet compares the identification of this received packet with those stored in its *Multicast_Message_Duplication_Table*.

We consider this phase as a modified form of the route request in DSR protocol. The major mismatch arises in the mean of applying the source routing concept. In our case, the source route accumulates in the *Join-reply* packet during the reply phase instead of being accumulated in the request phase. Thus, we eliminate the channel and routing overhead. In addition, the propagation of the *Join-request* does not stop whenever a receiver is reached as in the DSR unicast case, however it continues in order to cover all the receivers of the multicast group.

Sequence number	Source ID	Destination ID

Figure 5.1 Format of the Join-request packet

5.3.2 Reply Phase and FG Nodes Selection

The reply phase is initiated through sending a *Join-reply* packet by the first multicast receiver that receives the *Join-request* packet. Figure 5.2, shows the *Join-reply* packet format. It stores the multicast group ID in a *Source ID* field and the ID of the requesting node (source of *Join-request*) in a *Destination ID* field. A source route from the multicast receiver (source of *Join-reply*) to the requesting node (multicast source) accumulates in a *Route record* field during the *Join-reply* propagation. An explanation diagram for the mesh creation process is provided in Figure 5.3, showing the reply phase and the FG nodes selection. A multicast receiver, receiving a *Join-request* packet, first checks its *Neighbor_Stability_Table* for stability information among its neighbors (association stability, link signal strength, and link availability). Battery life is also verified considering the consumed power needed to transmit to each neighbor. A neighbor is selected as an FG node if the four selection metrics satisfy their predefined thresholds. Then, the receiver starts sending a *Join-reply* packet to each selected node setting its type as member node in the *Neighbor_Stability_Table*. If there are no neighbor nodes satisfying the predefined thresholds, we assume that the node with the best metrics among all the neighbors will be selected as an FG node.

Source ID	Destination ID	Route record

Figure 5.2 Format of the Join-reply packet

An FG node, receiving a *Join-reply*, first creates an entry to the multicast group in its *Multicast_Routing_Cache*. In this entry, the node sets its state as an FG node and copies the reversed accumulated route of the received *Join-reply*. It also stores the source of the *Join-reply*, and the time at which the packet is received. Then it performs the same previous steps for selecting FG nodes among its neighbors. This process continues until reaching the source, constructing a mesh of FG nodes that connect group members.

When the source receives the *Join-reply* packet, it becomes a multicast source for the group and it creates an entry to the multicast group in its *Multicast_Routing_Cache*. More than one *Join-reply* may be received by the source for the same multicast group (basic idea of the mesh topology), hence, multiple routes can be stored for the same multicast group.

An FG member node, having an unexpired route to the multicast group in its *Multicast_Routing_Cache*, can also reply to newly generated *Join-request* packets, whether for the same multicast group or for other multicast groups. At this case, the FG node starts transmitting a *Join-reply* packet to the source of the *Join-request* with the route record field taken as the stored route in its *Multicast_Routing_Cache* while adding the node's ID to this route. Then, the process of *Join-reply* forwarding proceeds as previously mentioned until reaching the multicast source. Thanks to the source routing concept, loop formation is prevented during *Join-reply* propagation.

As a mean of mesh maintenance, each multicast receiver initiates the reply phase every predefined period of time. The main idea is keeping the most recent and correct routes in the mesh, while purging the expired ones.

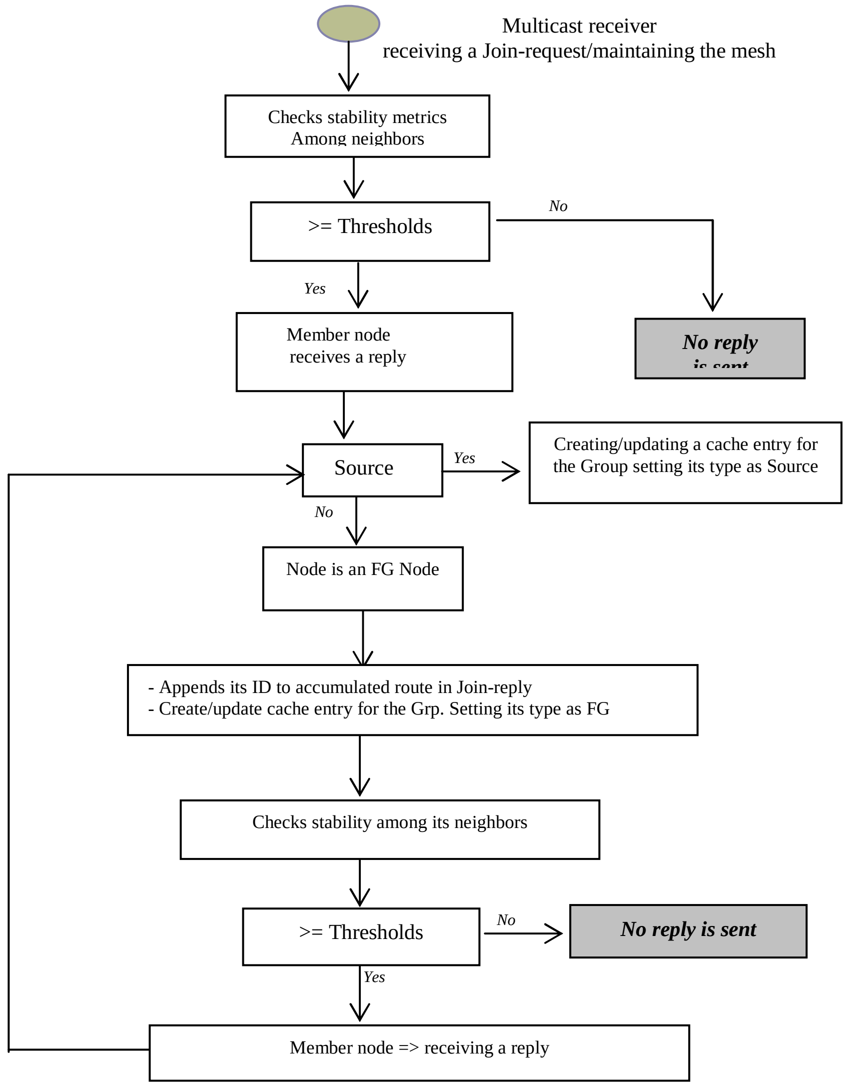


Figure 5.3 Reply Phase and Mesh Establishment

5.3.3 Data Forwarding

Figure 5.4 shows the data packet format. It carries in its header the selected route indicating the sequence of hops to be followed in the *Route record* field. The *Source ID* field stores the ID of the multicast source transmitting the data packet, while the multicast group ID is stored in the *Destination ID* field. A sequence number is generated by the source for each transmitted data packet and is stored in the *Sequence number* field; and is used by each node to detect duplication at each data packet reception through checking its *Multicast_Message_Duplication_Table*

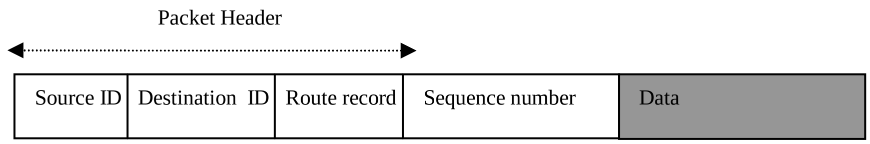


Figure 5.4 Data packet format

An explanation diagram is provided in Figure 5.5, showing the process of data transmission and forward upon the created mesh topology. A multicast source starts transmitting its data making use of the routes stored in its *Multicast_Routing_Cache* towards the multicast group. Each FG node receiving a data packet forwards this packet if it has stored in its cache at least one valid route towards the multicast group and the packet is not duplicated. This leads to an attractive feature in SRMP, preventing packets transmission through stale routes and minimizing traffic overhead. This process continues to transmit data to all multicast receivers.

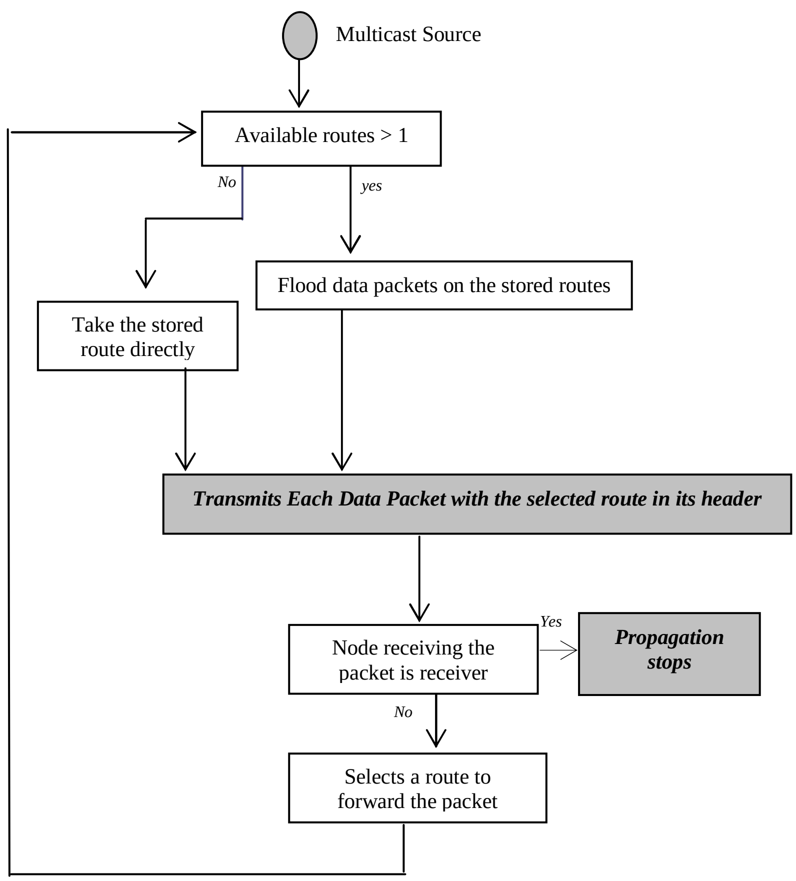


Figure 5.5 Data Forwarding

A multicast receiver, receiving a data packet for the first time, creates an entry in its *Receiver_Multicast_Routing_Table*. The route to the multicast source is stored in this entry via copying the reversed route stored in the *Route record* field of the received data packet. This entry is refreshed during continuous reception of data packets from this source; Section 5.4.2, gives a detailed description of mesh refreshment.

5.3.4 Descriptive Example

Figure 5.6, provides a descriptive example as a mean of demonstrating the protocol's operation. For simplicity, we assume that there is only one multicast group with a multicast address equal to **01**. We consider **S** as the multicast source wishing to join the group and ($\mathbf{R_1}$, $\mathbf{R_2}$) as the multicast receivers of the group.

In Figure 5.6(a), we show the route discovery process. S broadcasts a *Join-request* packet to its neighbors. Meanwhile, duplication of *Join-request* is detected and discarded. First, node S broadcast the *Join-request* to its neighbor nodes (x, y, and z). Each neighbor in its turn starts to broadcast the packet to its neighbors until reaching the receivers; at the same time duplication in reception is detected and ignored at (x, y, z, and R_1). The reply phase is then started at each receiver (R_1, R_2) as shown respectively in Figure 5.6(b) and Figure 5.6(c). In this process, nodes X and Y are selected as FG nodes, following SRMP selection criteria and constructing the mesh.

During the *Join-reply* propagation, cache entries are created or refreshed at each node. First R_1 sends its *Join-reply* (assumed at time 1) to X and Y, nodes X and Y start to store in their caches a new entry [01 FG 01 1] indicating the route to the multicast group. Then R_2 sends its *Join-reply* (assumed at time 1.5) to node Y, node Y will update the timer of its cache entry [01 FG 01 1] refreshing the same route to the multicast group. The process of *Join-reply* transmission continues in the same way until the source, storing or refreshing routes in each node's cache.

The created mesh is shown in Figure 5.7. **X** and **Y** are selected as FG nodes during the reply phase from the multicast receivers $\mathbf{R_1}$ and $\mathbf{R_2}$ to the multicast source **S**.

Figure 5.8 illustrates the data transmission from the multicast source **S** to the multicast receivers $\mathbf{R_1}$ and $\mathbf{R_2}$. Firstly, **S** starts transmitting its data packets using the stored routes in its *Multicast_Routing_Cache*, meanwhile the timer of each used route is refreshed. When these transmissions reach the FG nodes (**Y** and **X** respectively), the FG nodes continue forwarding the data packets, until reaching the multicast receivers, and the corresponding routes are refreshed in their *Multicast_Routing_Cache*.

When $\mathbf{R_1}$ and $\mathbf{R_2}$ receive the first data packet from the multicast source **S**, they create an entry in their *Receiver_Multicast_Routing_Table* towards this source. This entry stores the multicast group ID, multicast source, the route toward this source (reversed route stored in the received data packet). The time of packet reception is stored in the timer field, which is refreshed at each data packet reception. During the continuous reception of data packets, duplication is detected at $\mathbf{R_1}$ and $\mathbf{R_2}$ and discarded, as shown in Figure 5.8.

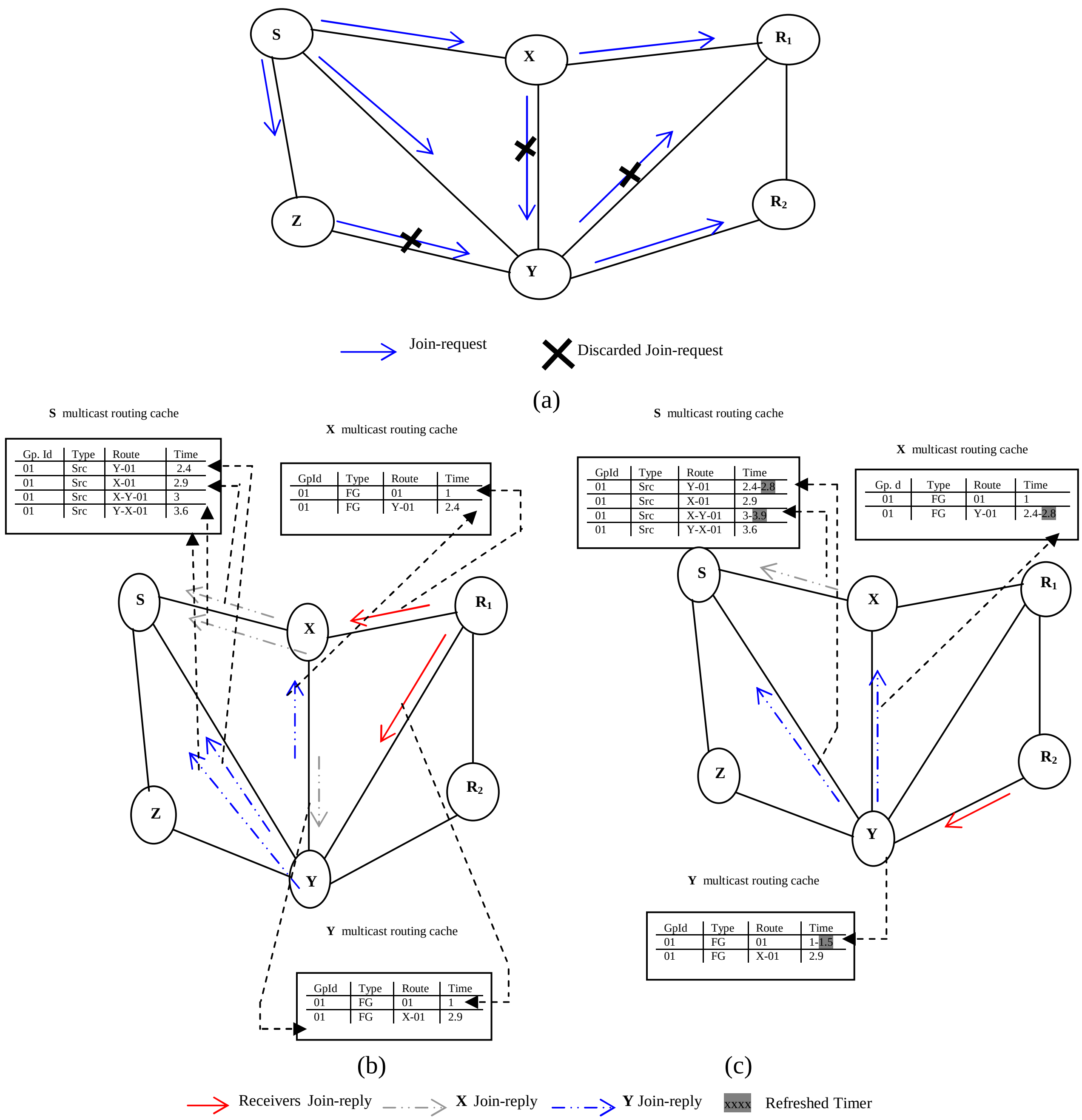


*Figure 5.6 : A Small Network Running SRMP: (a) Join-request generation by **S**, (b) Join-reply generation by **R_1** to **S**, and (c): Join-reply generation by **R_2** to **S***

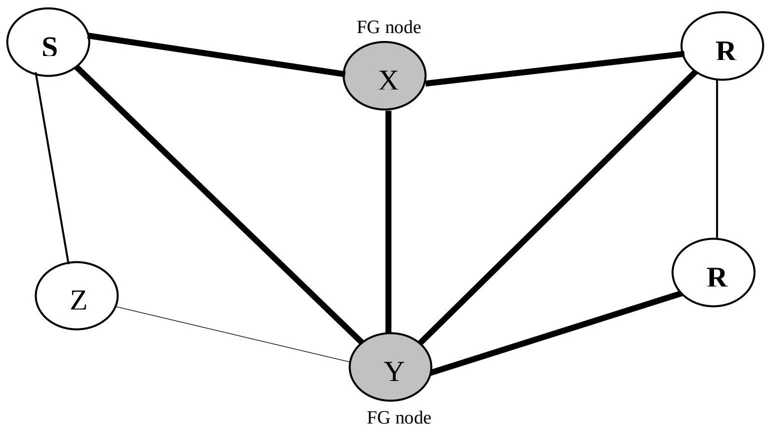


Figure 5.7 Mesh Creation

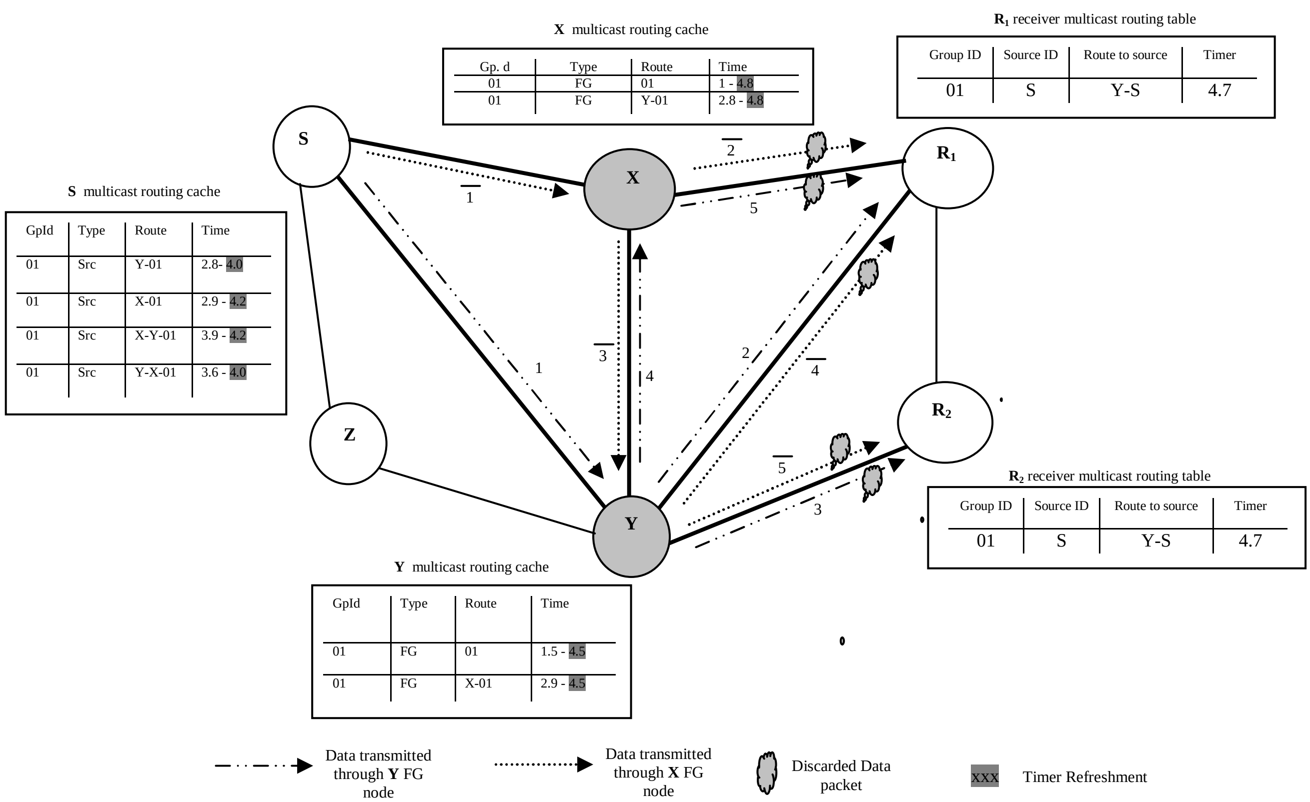


Figure 5.8 Data Transmission and Forward

5.4 SRMP Maintenance Procedures

Due to host mobility and/or interference, an established route may be broken. Route maintenance should report routing problems and recover them. To achieve this, SRMP introduces several mechanisms including node-neighbors information, mesh refreshment, multicast mesh reconfiguration and member node pruning. We address several mechanisms in which the multicast mesh is refreshed, link breaks are detected and repaired, continuous node-neighbor information is provided, and pruning is supported allowing any node to leave the group. Our goal is to keep the lifetime of a route as long as possible. We make use of the MAC layer beacons and introduce two new messages: the *Multicast-RERR* Message, and the *Leave_Group* Message.

5.4.1 Neighbor Existence Mechanism

SRMP uses the MAC layer beacons to provide each node with information about its neighbors' existence. When a node receives a neighbor's beacon, it updates or creates the corresponding entry of this neighbor in its *Neighbor_Stability_Table*. Entry update takes place through incrementing the *associativity ticks* field, and setting the *signal strength* field according to the level of strength the beacon is received. In addition, the node performs continuous prediction for link's availability towards the neighbor and updates its *link availability* field. If no beacons are received by a node from a certain neighbor up to a certain period of time, the node indicates neighbor's movement and updates its stability table fields towards this neighbor through setting the *associativity ticks* field to **zero** and *signal strength* and *link availability* fields to **null** until it receives new information from this neighbor.

5.4.2 Mesh Refreshment Mechanism

SRMP follows a simple mechanism in refreshing its mesh, making use of data packets propagation and requiring no extra control overhead. During data packets' propagation, route refreshment for different paths on the mesh takes place. Each time the source transmits a data packet it updates in its *Multicast_Routing_Cache* the timer of each route used. Typically, an FG node forwarding this packet scans the packet header, and refreshes in its *Multicast_Routing_Cache* the corresponding route entry timer. A multicast receiver also scans the header of each received data packet, refreshing its corresponding *Receiver_Multicast_Routing_Table* entry timer to the source. Furthermore, multicast receivers re-initiate the reply phase at each predefined period of time as previously mentioned in Section 5.3.2, where each intermediate node as well as the source update their cache entries during this phase. Through this mechanism, we allow the existence of the most recent and correct routes in the mesh. We guarantee that no stale routes are stored. Periodically, each node checks its timers and purges out expired multicast group entries.

5.4.3 Link Repair Mechanism

Mesh reconfigurations are required to adapt the multicast mesh to the movement of any mesh member node. SRMP reacts to nodes' mobility on-demand, such that it detects link failure, through the use of MAC layer support, during data transmission on the mesh. We address two mechanisms: (i) how to maintain routes when a link fails between two FG nodes, and (ii) how to maintain routes when a link fails between a multicast receiver and an FG node. We assume that the mesh reconfigurations are not needed if the stability characteristics together with high battery life paths are valid throughout the lifetime of the multicast communications.

When link failure occurs between two FG nodes, SRMP follows the same concept proposed in the DSR unicast protocol. In this case, the node detecting the failure reports it to the original source of the data packets. First, it generates a *Multicast-RERR* packet indicating the broken link. Then, it deletes from its cache any route containing the broken link. Nodes on the way to the source, receiving this packet, clean in their turn their *Multicast_Routing_Caches* from all routes containing the broken link. The format of the *Multicast-RERR* packet is shown in Figure 5.9, where the *Type* field indicates whether he node is an FG node or a multicast receiver.

Type	Group ID	Broken Link	Route to sender

Figure 5.9 Format of the Multicast-RERR packet

Otherwise, if a link failure takes place between an FG node and a multicast receiver, the FG node detecting the failure simply deletes the receiver membership from its *Neighbor_Stability_Table*. Then, a *Multicast-RERR* packet is sent to all member neighbors reporting the failure, where the *Route to sender* field in this packet is set to the member neighbor address. Each member neighbor, receiving this packet, cleans in its turn its *Multicast_Routing_Cache* from routes containing this broken link. The process is repeated until all member nodes in the mesh are visited. During the protocol's operation, each FG node continuously checks its *Neighbor_Stability_Table* and deletes from its *Multicast_Routing_Cache* any routes to multicast groups possessing no more members.

Figure 5.10 shows two examples for link failures, which address respectively the two above mechanisms. Figure 5.10 (a), demonstrates an example of the link failure between two FG nodes. During data transmission on the path [**S-L-M-X-01**], the link **M-X** is broken between the two FG nodes **M** and **X**. Firstly, **M** detects the failure and sends a *Multicast-RERR* packet to the original source of the data packet, storing the link **M-X** in the *broken link* field, while it stores the reversed route accumulated in the data packet header [**L** – **S**] in the *route to sender* field. Secondly, **M** deletes from its *Multicast_Routing_Cache* all the routes containing the broken link. When node **L** receives the *Multicast-RERR* packet, it performs the same operation for deleting its *Multicast_Routing_Cache* entries containing the broken link then it forwards the packet to the next node in the *Route to sender* field, which is the source **S**. Then, **S** deletes in its turn all routes containing the broken link from its *Multicast_Routing_Cache*.

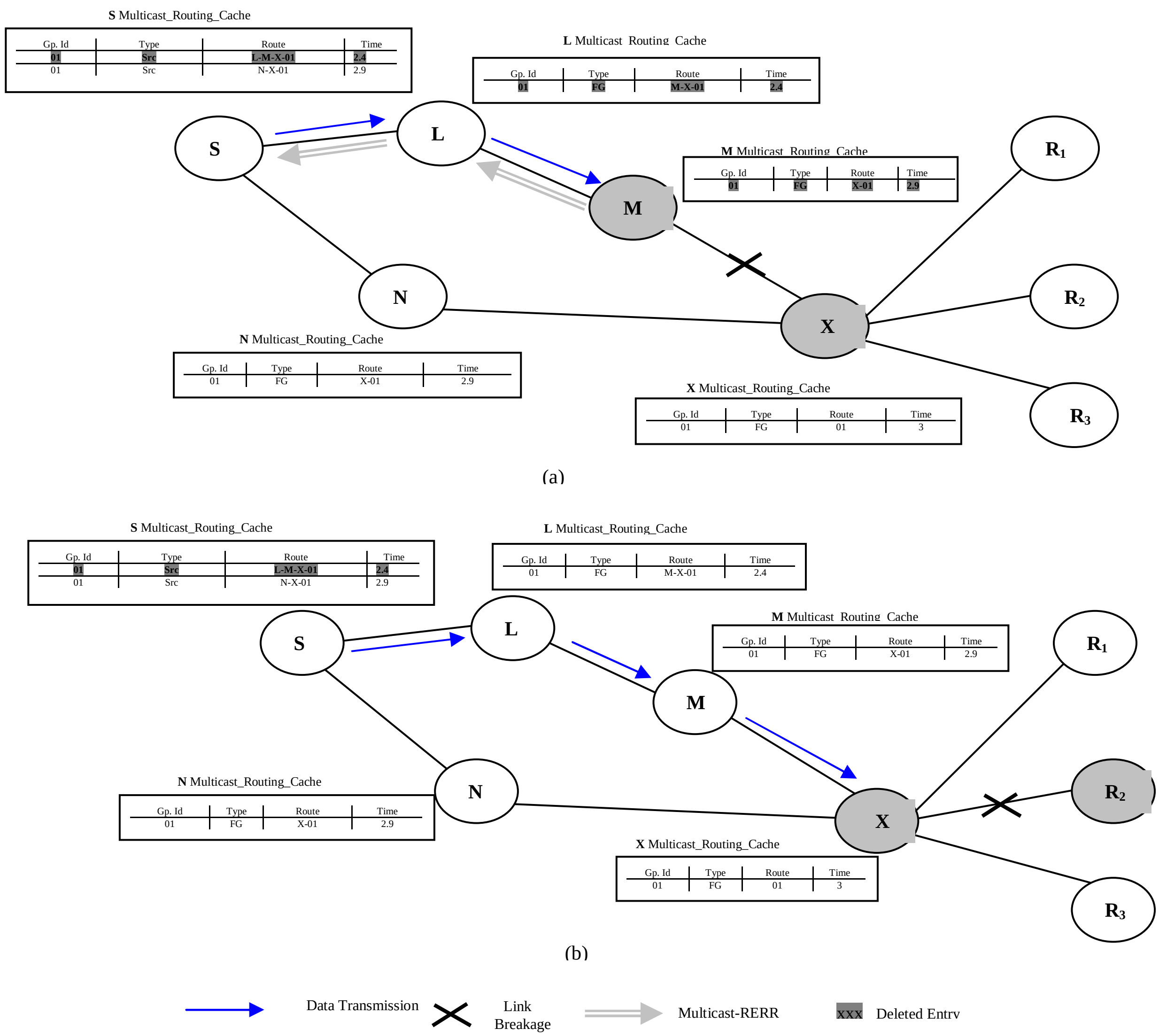


Figure 5.10 Link Failure Examples: (a) Link breakage between two FG Nodes, (b) Breakage Between an FG Node and a Multicast Receive

Figure 5.10 (b), demonstrates an example of the link failure between an FG node and a multicast receiver. During data transmission on the path [**S-L-M-X-01**], the link **X-R_2** is broken between the FG node **X** and the multicast receiver **R_2**. Firstly, node **X** deletes the receiver **R_2** from its *Neighbor_Stability_Table*. If no entries exist for the multicast group **01** in node's **X** *Neighbor_Stability_Table*, **X** deletes from its *Multicast_Routing_Cache* all routes to this multicast group and sends a *Multicast-RERR* packet to **M** and **N**. The *broken link* field in this packet contains **X-01** and the *route to sender* field contains the address of **N** and **M** respectively. When **N** and **M** receives this packet, they delete from their *Multicast_Routing_Caches* all entries containing [**X-01**] then they repeat the same process via sending *Multicast-RERR* packets to their neighbors until reaching the source.

5.4.4 Pruning Scheme

SRMP employs a pruning mechanism allowing a member node to leave the multicast session. We distinguish two cases: (i) when an FG node wants to prune itself, and (ii) when a multicast receiver wants to prune itself.

We assume that a multicast source wishing to leave a multicast group simply stops transmitting data to the group, and deletes from its *Multicast_Routing_Cache* all entries for this group. This results in an expiration of all routes connecting the source to the multicast receivers, due to non-refreshment of these routes. Similarly, the *Receiver_Multicast_Routing_Table* entries towards this source are expired and deleted.

On the other hand, a multicast receiver wishing to leave a multicast group sends a *Leave_Group* message to all its member neighbors, and deletes from its *Receiver_Multicast_Routing_Table* all entries for this group. A member neighbor, receiving this message, cancels in its turn the receiver membership from its *Neighbor_Stability_Table*. If the *Neighbor_Stability_Table* of the member neighbor contains no more members for the multicast group, all routes towards this group are deleted from the member neighbor *Multicast_Routing_Cache*. Then, a *Multicast-RERR* message is in turn sent to all its member neighbors following the previous link failure procedure.

Furthermore, an FG node wishing to leave a multicast group sends a *Leave_Group* message to its neighbors, deleting from its *Multicast_Routing_Cache* all entries for the multicast group. Figure 5.11 gives the format of this message. The multicast group ID is stored in the *Multicast group ID* field, the *Neighbor ID* field stores the ID of the member neighbor to which the message is sent. Each neighbor receiving this message cancels the FG node membership from its *Neighbor_Stability_Table*, deletes routes containing this node from its *Multicast_Routing_Cache*, and then sends a *Multicast-RERR* message to its member neighbors with the *Broken link* field storing the FG node, and the previous procedure of link failure are followed.

Multicast group ID	Neighbor ID

Figure 5.11 Format of the Leave Group

Figure 5.12 demonstrates an example of nodes' pruning in SRMP, showing respectively a multicast receiver pruning and an FG node pruning.

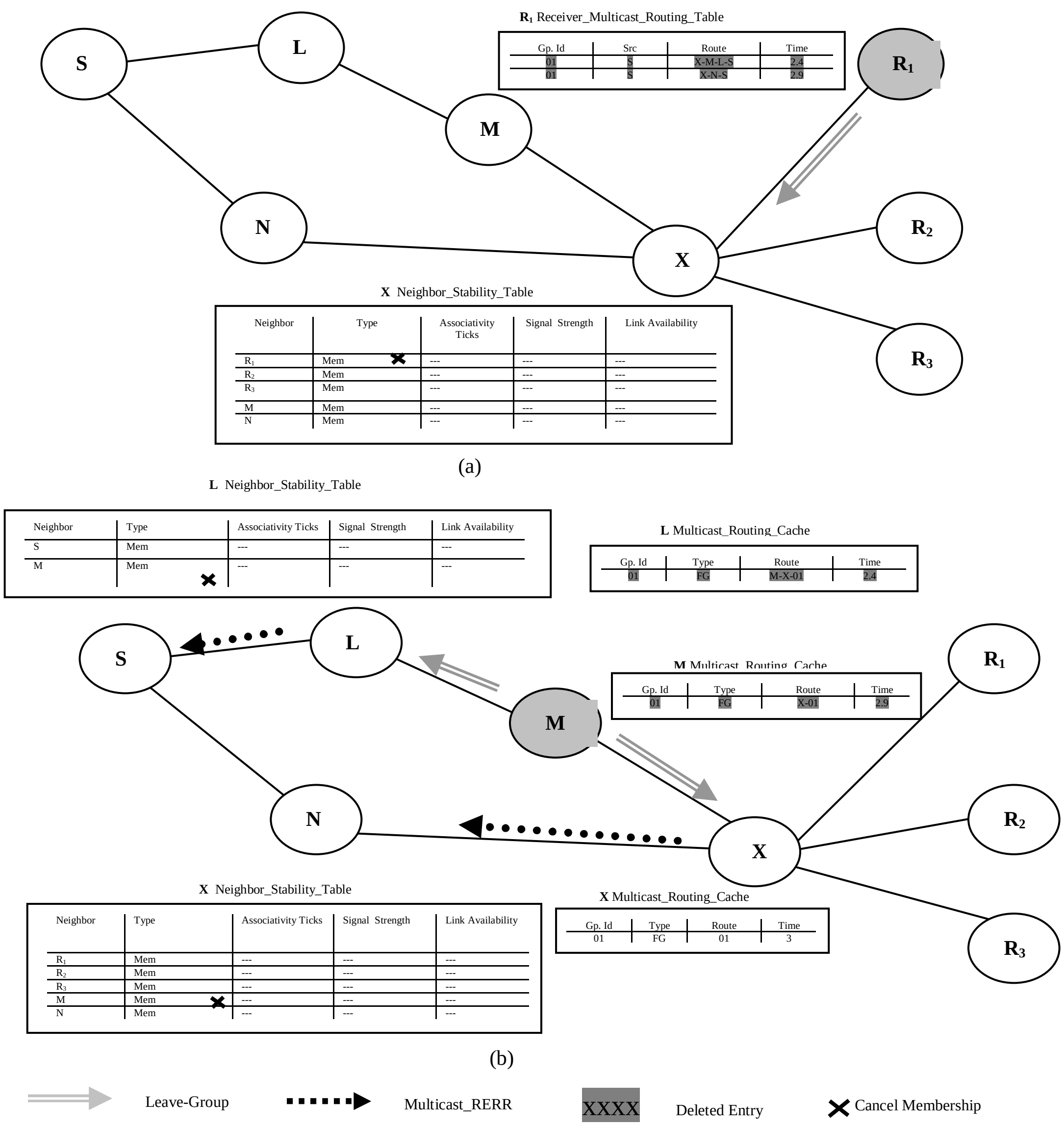


Figure 5.12A Pruning Example: (a) Multicast Receiver Pruning, (b) An FG Node Pruning

In Figure 5.12 (a), the multicast receiver $\mathbf{R_1}$ wants to leave the multicast group. It deletes from its *Receiver_Multicast_Routing_Table* all entries for this group. Then, it sends a *Leave-Group* message to its member neighbor **X**, where **X** sets **R_1** as non-member node in its *Neighbor_Stability_Table.*

In Figure 5.12 (b), the FG node **M** wants to leave the group. First, **M** deletes its *Multicast_Routing_Cache* entries for this group. And it sends a *Leave-Group* message to its member neighbors **L** and **X**, where they set node **M** as non-member in their *Neighbor_Stability_Tables*. Then, node **L** deletes from its *Multicast_Routing_Cache* all entries containing node **M**. Indeed, node **X** will do nothing, as it does not have route entries in its *Multicast_Routing_Cache* containing node **M**. Then, both nodes send *Multicast-RERR* packet to their member neighbors (**S** and **N** respectively) following the previous procedure of link failure.

5.5 Features

SRMP is an on demand mesh based multicast protocol. Route construction and membership maintenance are carried out in an on demand manner, thus avoiding periodic channel and routing overhead. The FG nodes concept is applied during the construction of the mesh to connect group members.

The Key advantages of SRMP are the robustness and richer connectivity, low channel overhead, connectivity quality, and lower energy consumption.

Our protocol is also characterized by the following properties:

- Efficient use of network resources due to on-demand approach.
- The use of source routing allows loop free packet routing.
- Avoiding the drawbacks of multicast trees.
- Redundant paths are available due to mesh structure, thus decreasing the frequent rerouting required for data in case of link breakage.
- Duplication is detected in data packets, which decreases channel overhead.
- FG nodes concept is used in mesh creation, limiting the flooding scope and reducing channel and storage overhead.
- The criteria used to select FG nodes provides paths with links stability and availability according to future prediction, this allows SRMP to provide optimum paths in terms of communication overhead, reliable delivery, and quality of connections.
- Higher battery life paths are also chosen, which preserves battery life of other nodes having lower battery level.

- Efficient refreshment mechanism is used to maintain the mesh structure during data transmission. This mechanism requires no extra control overhead, since it makes use of data propagation to refresh the used routes.
- Timers are also used to prevent stale routes in the nodes tables.
- Effective mechanism is used for pruning, preventing the existence of stale routes.

As a means of vindicating our proposition, we focus on comparing it with ODMRP, as it is a mesh-based protocol. In fact, SRMP achieves some characteristics that do not exist in ODMRP. SRMP outperforms ODMRP in its effective mesh refreshment mechanism, making use of data propagation and requiring no extra control overhead. Meanwhile, ODMRP depends on periodical (*Join-Query*/*Join-Reply*) to refresh route entries constituting the mesh. In addition, the request/reply phase in SRMP is more efficient, because the request is sent once by a source wishing to join the group, and small size reply packets are sent in the reply phase. ODMRP follows a different approach by using periodical *Query/Reply* during the period of data transmission requiring more control and communication overhead. Furthermore, it transmits a reply table with multiple reply entries to different sources causing reliability problems, such that the verification of the *Join-Reply* delivery that may not be handled by the MAC layer and special mechanisms are required to overcome this problem.

In terms of link breakage, ODMRP has no special mechanism; it only assumes that a receiver wanting to move would stop sending replies. On the other hand, SRMP possesses an effective link breakage mechanism to discover unavailable routes and delete them from nodes caches. It also uses a special pruning mechanism allowing mesh members to leave the group at any time, which is not the case in ODMRP.

5.6 SRMP Performance Evaluation

In this part, we evaluate the performance of our proposed on-demand mesh-based multicast routing protocol SRMP, proving the usefulness of its mechanisms for multicast routing in an ad hoc environment.

Our goal is to investigate SRMP performance behavior under a wide variety of simulation scenarios including: network configurations, multicast group compositions, and mobility types and models. Also, we compare its performance with both ODMRP and ADMR protocols showing the efficiency of our approach. We chose ODMRP because it uses the mesh structure in forwarding multicast packets, and ADMR because it uses more classical multicast forwarding trees.

Our evaluation study comprises:

- An implementation of SRMP protocol in *ns*-2.

- A comprehensive evaluation of SRMP, ODMRP, and ADMR in terms of specific performance metrics and under different mobility types and network configuration.
- A performance study of SRMP in a scalable network environment.
- A performance evaluation of SRMP under different mobility models.

In Section 5.6.2, we conduct a comparison study of SRMP versus ODMRP and ADMR in a 20-node network configuration. In Section, 5.6.3 we carryout a comparison study of the three protocols in a 30-node network configuration. We provide an energy-based evaluation for SRMP in Section 5.6.4, validating its energy conserving mechanism in a scalable network configuration. In Section 5.6.5, we evaluate SRMP performance using different mobility models, providing realistic conditions. We summarize our obtained results in Section 5.7.

5.6.1 Simulation and Performance Metrics

Our experiments are conducted in a common wireless network simulation platform. We used the *ns*-2 network simulator [Fall98], where a mobility extension was developed by the CMU Monarch project's wireless and mobility extensions [Monb]. To simulate the mobile multicast routing in a wireless environment, we use a mobile multicast extension to *ns*-2, which is developed by the Rice Monarch Project [Mona]. Appendix A, covers the mobile wireless simulation environment in *ns*-2, and introduces some concepts in the implementation of multicast protocols under *ns-2*.

Throughout our analysis and study in the following sections, we studied various combinations of performance metrics, as a mean of evaluating SRMP performance. These performance metrics are:

Delivery Ratio: the ratio of the number of data packets actually delivered to the receivers versus the number of data packets supposed to be received.

End-to-End Delay: the latency between the origination of a multicast data packet by a source, and its successful reception by each multicast receiver.

Control Overhead: the total number of all control packets/bytes transmitted by any node in the network. This metric considers the overhead for all the originated control packets.

Link Failure: the total number of link breaks during the whole simulation time. This metric reflects the mesh reliability.

Link Failure Rate: the time between each consecutive link failures, we measure it along the whole simulation time and the average is taken.

Robustness: this is the nodes' robustness in terms of the number of valid routes at each node for the multicast group, divided by the number of receivers of the group. We calculate it for each pause time at different intervals along the simulation, and then the average is taken.

Energy Level: an energy level metric; considering the average current energy level for all nodes. It is calculated at the end of the simulation, showing the amount of battery consumed during the simulation. We measure it as a percent of the initial battery energy assuming that all nodes start with the same initial energy.

Data Retransmission Size: The total number of re-transmission, for the data packets, taking place at the MAC layer. We measure it for the whole simulation time.

Data Retransmission Rate: The rate of data packets re-transmission at the MAC layer. We calculate it during the whole simulation time, and then the average is taken.

5.6.2 A Comparison Study for a 20-Node Network

5.6.2.1 Simulation Model and Scenarios

The overall goal of our simulation study is to analyze the behavior of our protocol under a range of various mobility scenarios. Our simulations have been run using a MANET composed of 20 nodes moving over a rectangular 1200 m x 300 m space, and operating over 600 seconds of simulation time. Nodes in our simulation move according to the RWP mobility model. The movement scenario files used in each simulation are characterized by pause times. We studied 6 different pause times: 0, 30, 60, 120, 300, and 600.

Our performance evaluation is a result of 120 different simulations, using 20 different simulations for each pause time. At each pause time, we study runs with a maximum nodes movements' speed of 20 m/s and others with a maximum nodes movements' speed of 1 m/s. For each pause time and max nodes movements' speed, we randomly generated 10 different scenarios. The multicast traffic sources in our simulation are CBR traffic. Each traffic source originates 64 bytes data packets, using a rate of 4 packets/second.

We used 2 different compositions of multicast groups, sources, and receivers. In order to observe the behavior of the routing protocol in a simple environment consisting of a large number of receivers, we considered a first scenario with 1 multicast source and 10 multicast receivers. For evaluating the performance of our protocol with more than one multicast group, we used a second scenario consisting of 3 groups with 1 source and 3 receivers per source.

5.6.2.2 Results and Analysis

As a first step, we evaluated the performance of SRMP and compared it with ODMRP and ADMR in terms of end-to-end delay, delivery ratio, and control packets and bytes overhead. The obtained results are illustrated respectively in Figure 5.13 and 5.14.

Figure 5.13, shows the evaluation of the cited performance metrics as a function of pause time in the 1-source and 10 receivers scenarios. Concerning the delivery ratio in Figure 5.13(a), ODMRP and ADMR show nearly the same behavior. SRMP shows incremental delivery ratio starting from intermediate mobility, and outperforms ODMRP and ADMR starting from pause time 500, when the network tends to be stationary. This refers to the links' quality compared to ODMRP and ADMR.

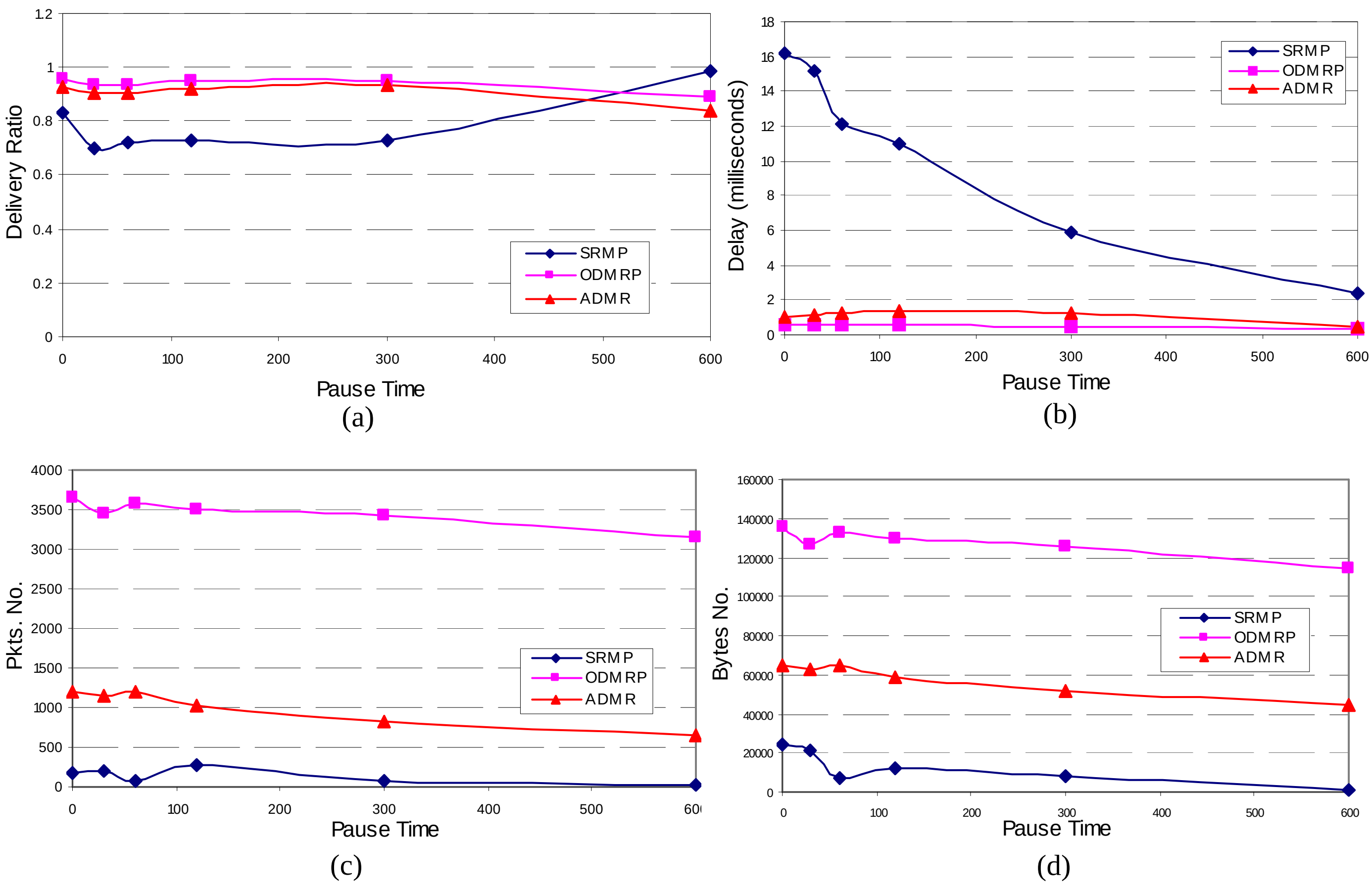


Figure 5.13 1 Source and 10 Multicast Receivers: (a) Average Delivery Ratio ,(b) Average End-to-End Delay, (c) Average Control Packets Overhead and (d) Average Control Bytes Overhead

The signal strength metric, used in the selection criteria while constructing the mesh allows SRMP links in this case to react better to interference and distortion that is frequent in ad hoc environment. In case of continuously moving nodes and intermediate mobility nodes, SRMP exerts less delivery ratio with no great impact. This is due to the network flood used in ODMRP, reducing the link breakage and route discovery and thus increasing the delivery ratio. Similarly, the use of tree and network flood to forward multicast packets in ADMR together with the shortest-delay path, increase the delivery ratio.

Figure 5.13(b), shows the transmission delay. ODMRP and ADMR show nearly the same behavior. SRMP shows an increase in delay in the case of very high mobility, this comes from the frequent application of the selection criteria to set up new links due to the high link failure rate. It is clearly noticed that this increase in delay drops fast with a slight decrease in mobility. Thanks to the selection criteria, SRMP is able to assure more stable, longer route lifetime, and higher battery life paths consuming less energy compared to the other two protocols. Using these paths, minimizes the probability of links' failure and paths reconstruction, substantially minimizes the protocol's overhead and provides more quality links reacting better in a radio environment.

Figure 5.13(c) and 5.13(d), respectively show the packets and bytes overheads. We notice that SRMP provides better results. This is due to the frequent network flood use in ODMRP. For ADMR, this refers to the network flood together with the overhead in its local and global repair mechanisms and the keep-alive messages adding to protocol overhead. On the contrary, SRMP shows fewer overheads thanks to its source routing approach. In fact, the use of extra header packets fields in ADMR and the large size *Join-table* in ODMRP compared to SRMP *Join-reply* packet, causes a worst performance compared to SRMP.

For the 3 sources and 3 receivers' scenario, SRMP depicts out nearly the same previous behavior as illustrated in Figure 5.14. In particular, the delay difference with respect to ODMRP and ADMR is minimized compared to the first scenario. This is due to the lower number of receivers for each source, decreasing the delay consumed during paths' selection. Moreover, SRMP outperforms ODMRP and ADMR at intermediate and low mobility, this refers to the strength and availability of the used links showing better effect for this mobility cases.

Figure 5.15 illustrates the behavior of SRMP and how it adapts to link failure relative to the two multicast group composition cases. We calculated the average link failure rate to show the robustness of the protocol for each scenario case. We notice that the average link failure rate decreases gradually with pause time increase for our two scenario cases, this results from the more frequency of links' break at the cases of higher mobility (smaller pause time). As the nodes' mobility increases, the more possibility of links' break takes place. Comparing the two cases, the (1 source/10 receivers) case has better impact on the average link failure rate than (3 sources/3 receivers per source) case. This is due to the construction of a denser mesh at the first case, constituting of a larger fraction of forwarding group nodes, which provides more robustness and increases the possibility of reaching multicast receivers due to the existence of more possible routes.

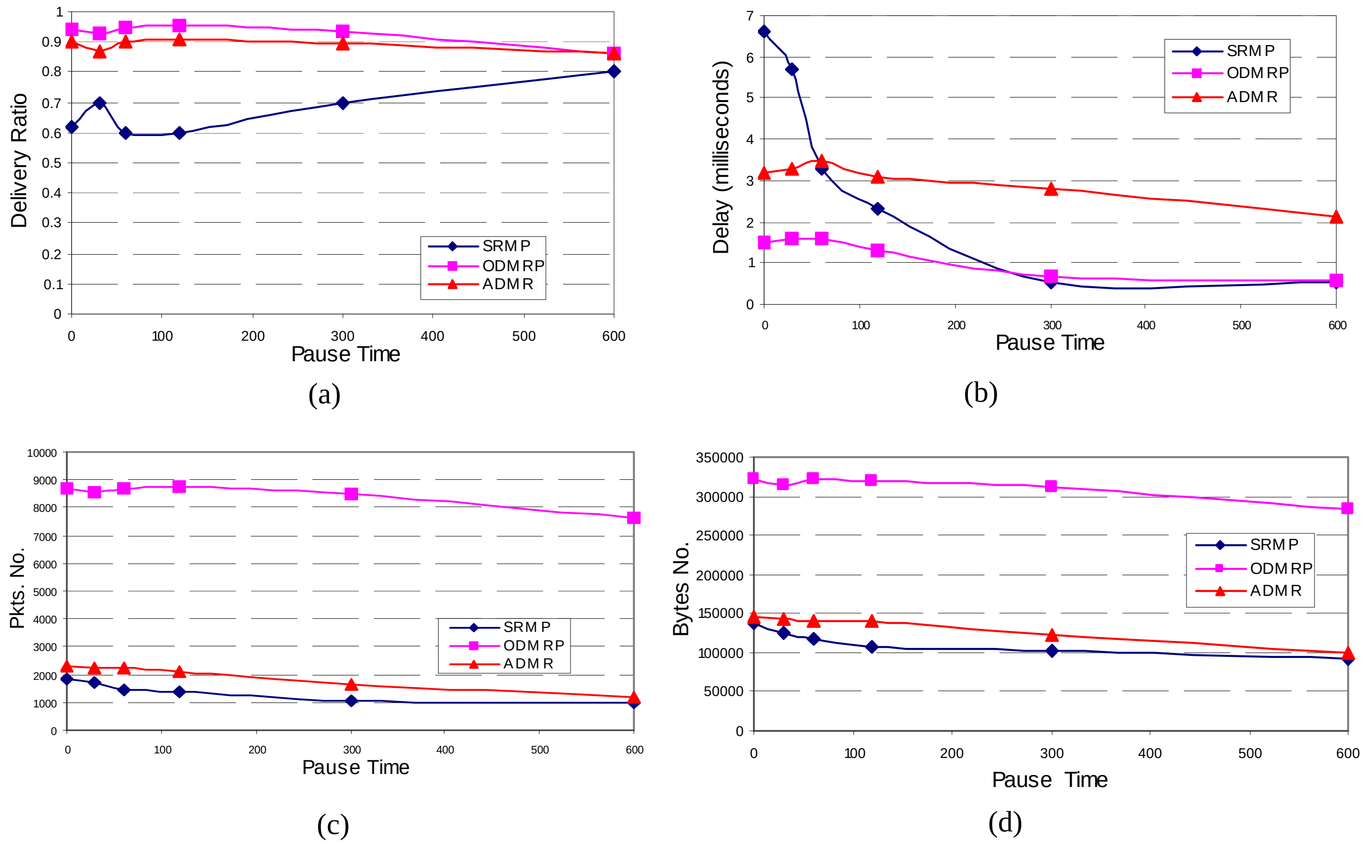


Figure 5.14 3 Sources and 3 Multicast Receivers Per Source: (a) Average Delivery Ratio, (b): Average End-to-End Delay, (c): Average Control Packets Overhead and (d): Average Control Bytes Overhead

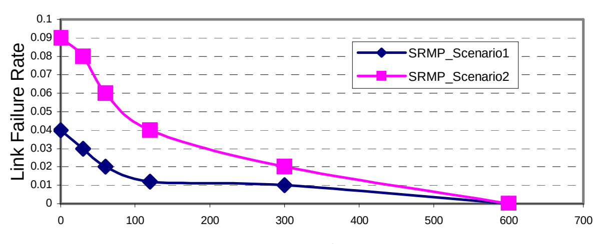


Figure 5.15 SRMP Link Failure Rate (Both Multicast Scenario)

To further study the robustness of our protocol, we chose to use another metric for robustness evaluation. In this context, we evaluated the nodes' robustness in terms of the number of valid routes, at each node, for the multicast group divided by the number of receivers of this group. We calculated robustness for each pause time at different intervals along the simulation time. Figure 5.16, indicates the average nodes robustness in case of (1 source/10 receivers) case. We see that robustness increases with pause time decrease, showing the efficiency of SRMP in maintaining routes towards the multicast receivers thanks to its stable mesh structure. At the highly dynamic network case (pause time 0-100), best results are obtained due to the frequent route discovery following paths' failures. Thus allowing mesh re-construction selecting the most recent FG nodes to form stable paths.

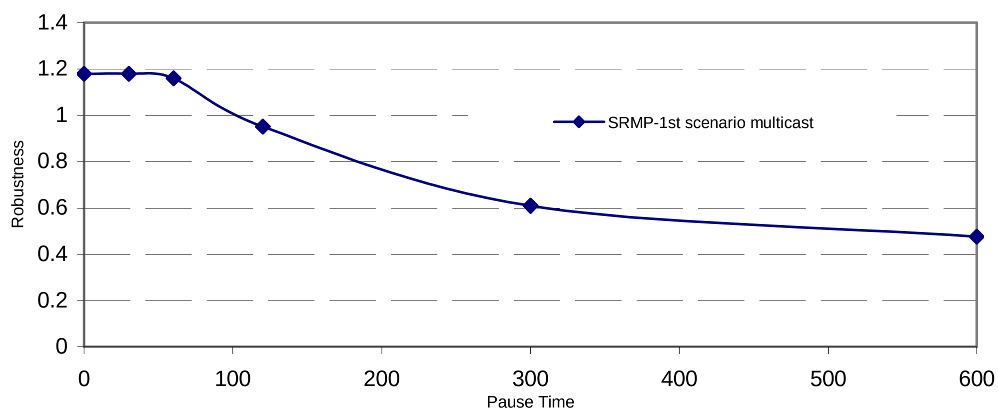


Figure 5.16 SRMP Robustness (1st Multicast Scenario)

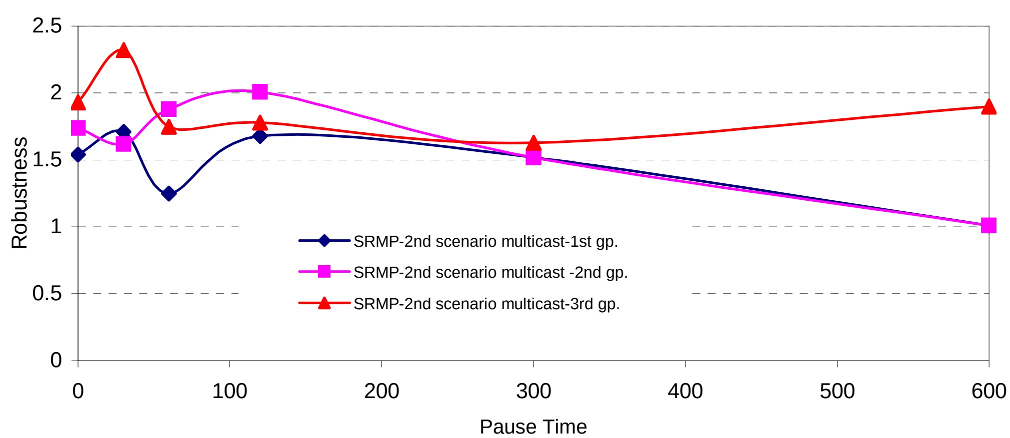


Figure 5.17 SRMP Robustness (2nd Multicast Scenario)

The same behavior is nearly shown for the (3 sources/3 receivers per source) case in Figure 5.17. The difference is that the group robustness value is higher compared to the first case. This is due to the small number of receivers compared to the first scenario. Regarding the 3 multicast group of this case, they have nearly the same behavior with different pause times. The little difference between them in the robustness value is due to the various composition of each multicast group in terms of time of (Join and Leave) of each multicast receiver.

Finally, Figure 5.18 shows SRMP efficiency in energy consumption. We used energy level metric in our evaluation; which is the average energy level for all nodes. It is calculated at the end of the simulation, showing the amount of battery consumed during the simulation. We measured it as a percent of the initial battery energy assuming that all nodes start with the same initial energy. It is clear that this consumption is lower (higher energy level) in case of higher mobility cases compared to lower mobility cases, this is due to more robust mesh in these high mobility cases. Thus the transmission and forwarding are widely distributed on the different mesh paths. On the contrary, as the mobility decreases, the robustness decreases causing more traffic on the mesh and consuming more energy at each node. Energy level is better in case of intermediate mobility showing lower consumption, where there is more probability for stable paths to exist allowing better traffic distribution. Comparing the two multicast scenario cases, energy consumption is more in the second multicast scenario case due to the existence of 3 multicast groups. More energy is consumed to discover and construct routes towards each group, implying more transmission and forwards corresponding to the 3 traffic sources.

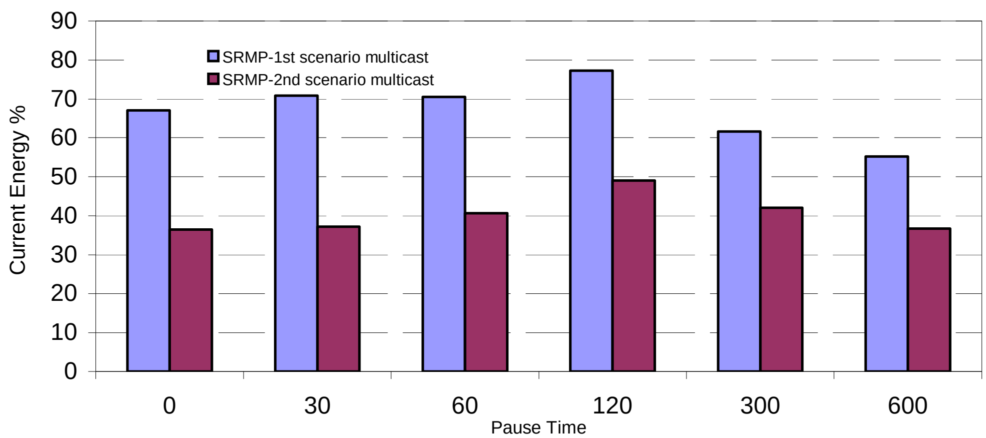


Figure 5.18 Energy Level (Both Multicast Scenario)

In this section, we evaluated the performance of SRMP compared to ODMRP and ADMR. At the same time, we evaluated the SRMP robustness and energy consumption.

As SRMP uses no periodic network flood of control packets, thanks to its selection criteria in mesh construction, stable paths with future links availability and higher battery life are provided. This assures better quality of links and minimizes the possibility of links' failure and the overhead needed to re-construct the paths.

We obtained remarkable results in favour of SRMP in this section. Firstly, our protocol showed significant decrease in the control overhead; its impact on the delay is acceptable depending on the mobility type, and it outperformed ODMRP and ADMR at intermediate and low mobility cases. In addition, SRMP provides an incremental delivery ratio starting from intermediate mobility.

Through our study and analysis, it is also observed that our protocol is efficient in terms of minimum energy consumption and nodes' robustness. Thus, SRMP tackles two of the main important features to be addressed in a suitable multicast protocol.

5.6.3 A Comparison Study for a 30-Node Network

After evaluating SRMP performance in Section 5.8, comparing its behavior with respect to ODMRP and ADMR, the aim of our performance analysis, in this section, is to evaluate the performance of SRMP and test its efficiency in a larger network. In addition, we aim at comparing its performance with both ODMRP and ADMR. We always choose ODMRP and ADMR, as they are two prominent multicast routing protocols.

5.6.3.1 Simulation Model and Scenarios

We run our simulations using a MANET composed of 30 nodes moving over a rectangular 1200 m x 800 m space, and operating over 600 seconds of simulation time. We run our simulations assuming the nominal transmission range which is equal to 250 m and we modified the physical layer from the base *ns*-2 distribution to increase the transmission rate from 2 Mbps to 4 Mbps. Nodes in our simulation move according to the RWP mobility model. The movement scenario files used in each simulation are characterized by 6 different pause times from hyperactive network to stationary network: 0, 30, 60, 120, 300, and 600. We assume that all nodes start with the same initial energy at the beginning of each simulation, where we chose it to be sufficiently large and equal to 50 Joules.

Our performance evaluation is a result of 120 different simulations, using 20 different simulations for each pause time. At each pause time, we study runs with a maximum nodes movements' speed of 20 m/s and others with a maximum nodes movements' speed of 1 m/s. For each pause time and max nodes movements' speed, we randomly generated 10 different scenarios. The multicast traffic sources in our simulation are CBR traffic. Each traffic source originates 64 bytes data packets, using a rate of 4 packets/second.

We used 2 different compositions of multicast groups, sources, and receivers. We considered a first scenario with 1 multicast group, composed of 1 multicast source and 10 multicast receivers, as a mean of observing the behavior of the routing protocol in a simple environment consisting of a large number of receivers. Then we considered a second scenario composed of 3 multicast groups, each group has 1 multicast source and 4 multicast receivers, as a mean of evaluating the performance with several multicast groups composition.

5.6.3.2 Results and Analysis

In this section, we first evaluate the performance of SRMP and compare it with ODMRP and ADMR in terms of the delivery ratio, end-to-end delay, and control overhead. The obtained results are illustrated respectively in Figure 5.19, 5.20, and 5.21. Then, we evaluate in Figure 5.22 the energy consumption of SRMP with respect to ODMRP and ADMR via the energy level performance metric.

Due to the importance of bandwidth utilization on the efficiency of the multicast routing, we study the efficiency of the routing protocol in utilizing the scarse bandwidth. In this context, we introduce two other metrics in our evaluation, which are the ***data re-transmission size*** and the ***data re-transmission rate***. The data re-transmission size measures the total number of re-transmissions for the data packets, taking place at the MAC layer. The data re-transmission rate measures the rate of data packets re-transmission at the MAC layer, where we calculate it for the whole simulation time and then calculate the average. As we notice, both metrics are calculated at the MAC layer, and thus allowing us to evaluate the behavior of our routing protocol through studying its effect on the MAC layer, and compare it to ODMRP and ADMR in this context. The obtained results concerning this part are illustrated respectively in Figure 5.23 and 5.24.

Our obtained results for the delivery ratio are illustrated in Figure 5.19. We notice that ODMRP and ADMR exhibit nearly the same delivery ratio for the two cases of multicast group composition, see Figure 5.19(a) and 5.19(b). Delivery ratio of both protocols tends to decrease from intermediate to low mobility cases. On the contrary, SRMP delivery ratio increases linearly in the interval between intermediate mobility and stationary network, where it nearly reaches a 100% delivery ratio at the first multicast group composition case. SRMP delivery ratio surpasses those of ODMRP and ADMR starting from intermediate mobility, this is strongly satisfied in the first multicast group composition case

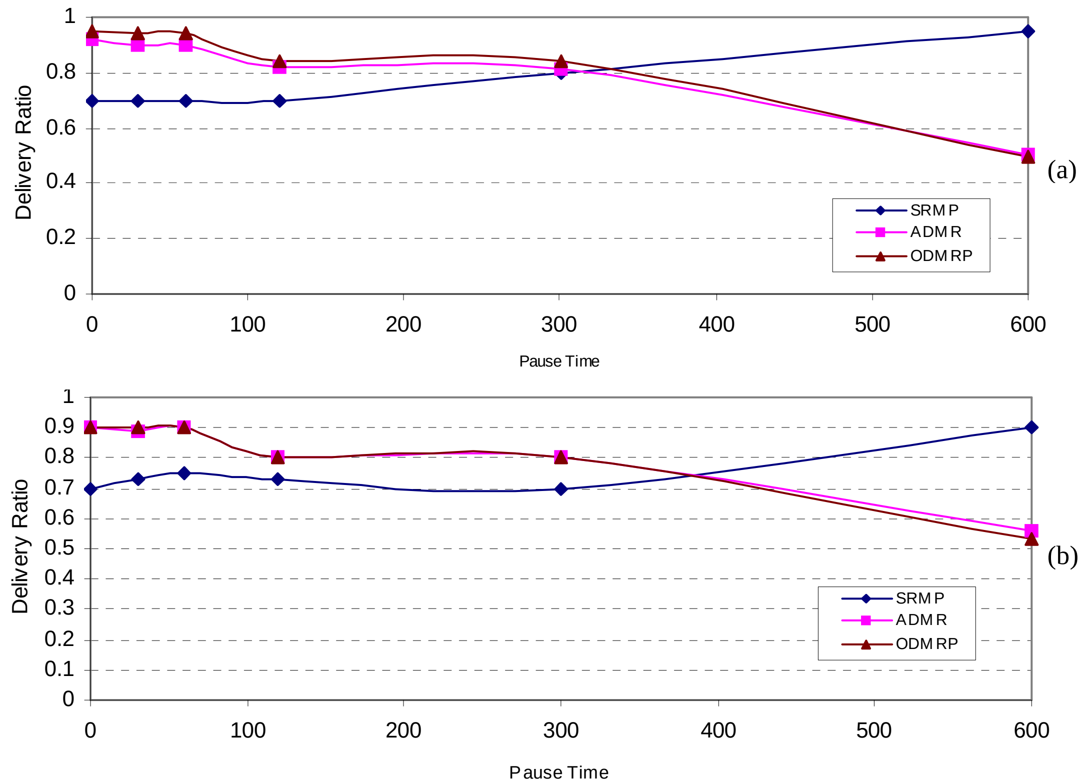


Figure 5.19 Average Delivery Ratio: (a) 1 Multicast Group Case and (b) Average Delivery Ratio: 3 Multicast Groups Case

In hyperactive and high mobility cases, SRMP shows lower delivery ratio compared to ODMRP and ADMR, but with no great impact. As noticed, SRMP delivery ratio is nearly constant, at these mobility states, for the first multicast group case (Figure 5.19(a)), and is nearly equal to 78% of the maximum delivery ratio attainable by ODMRP and ADMR. While in the second multicast group case, Figure 5.19(b), SRMP delivery ratio shows an increase with mobility decrease and is nearly equal to 80% of the maximum delivery ratio attainable by ODMRP and ADMR.

Our delivery ratio results are strongly in favor of SRMP for intermediate and low mobility network states. For continuously mobile networks, SRMP exerts less delivery ratio, which does not have a strong impact. The connectivity quality concept, which is the base of our approach in proposing SRMP, gives a great chance for the constructed links to react better and to have longer lifetime, which favors SRMP in intermediate and low mobility cases.

On the other hand, for high mobility cases, ODMRP and ADMR boast a higher rank. This fact comes as a result of the continuous flooding approach used in ODMRP and the use of network flood in ADMR to forward multicast packets, which assures a better delivery ratio in the case of the continuously mobile network constituting of short lifetime links.

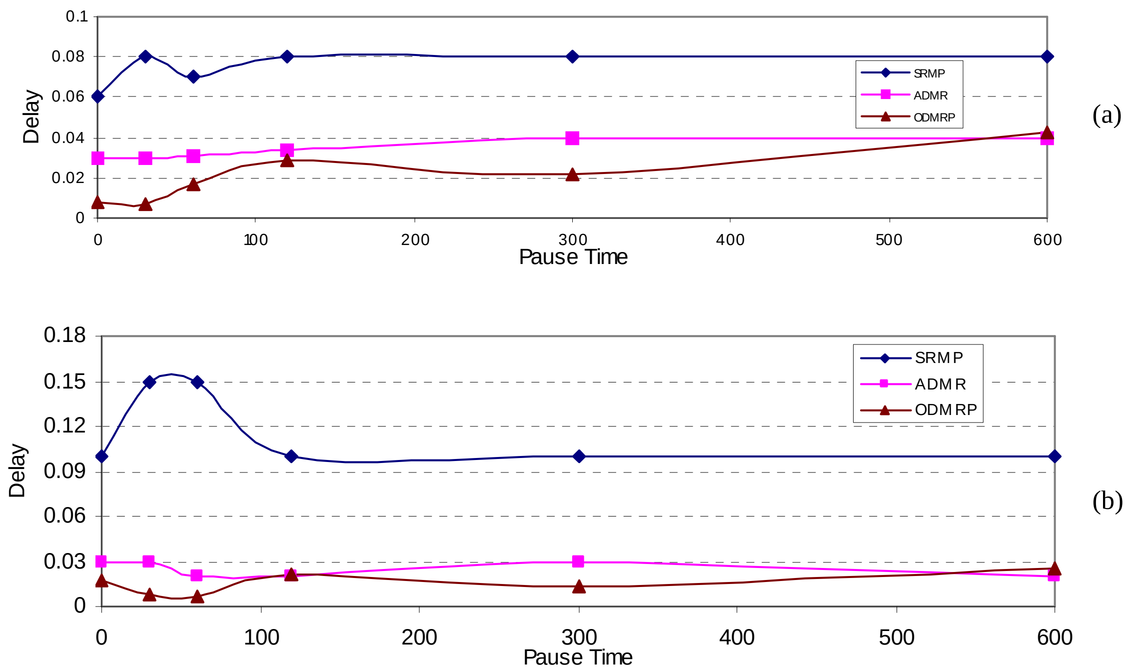


Figure 5.20 Average End-to-End Delay : (a) 1 Multicast Group Case and (b) 3 Multicast Groups Case

Figure 5.20 demonstrates the end-to-end delay for the three protocols. Although SRMP assures a connectivity quality during data transmission, it does not show a good rank concerning the end-to-end delay compared to ODMRP and ADMR. The weak performance of SRMP regarding the delay is due to the repetitive execution of the selection process during the mesh setup and maintenance. An interesting feature is that the SRMP delay is constant starting from pause time 120 until the stationary network state at both multicast group cases, see Figure 5.20(a) and 5.20(b). We observe that in the second multicast group case, this constant behavior follows a delay drop starting from pause time 60. Indeed, from pause time 60 to pause time 120, SRMP is able to assure more stable longer lifetime paths, minimizing link failure and thus minimizing the delay consumption in link repair and maintenance. This delay drop is not observed in the first multicast group case due to the large number of receivers, implying larger mesh and thus consuming more delay during the transmission on the mesh, even at lower mobility cases, and also during the mesh maintenance.

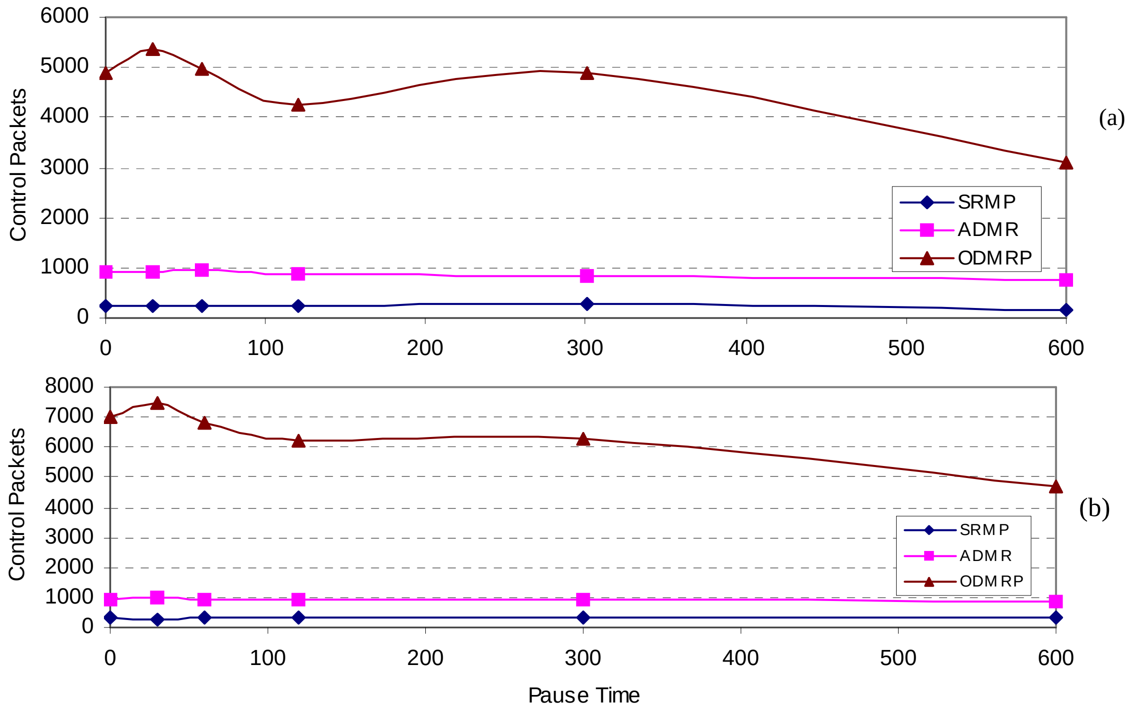


Figure 5.21 Average Control Packets: (a) 1 Multicast Group Case and (b) 3 Multicast Groups Case

In Figure 5.21 the control overhead is in favor of SRMP at the two multicast group cases and with all types of mobility. Actually, the minimized control overhead is one of the points of strength in SRMP that distinguishes it compared to the other protocols. This feature refers to the minimized flooding in SRMP, and also the minimized periodic messages sent. Furthermore, the source routing concept used in SRMP saves the overhead in discovering the next hop.

ODMRP has the maximum overhead in all mobility cases as well as in the two multicast group cases. This comes as a result of the ODMRP continuous flooding approach in addition to the periodic request/reply transmission during the construction of each mesh. This proves that ODMRP takes a weak rank with respect to its control overhead.

ADMR exhibits an intermediate overhead between ODMRP and SRMP. The reason of SRMP superiority also is the partial flooding approach invoked in ADMR together with its repair mechanism and the keep-alive messages sent that adds to the protocol overhead.

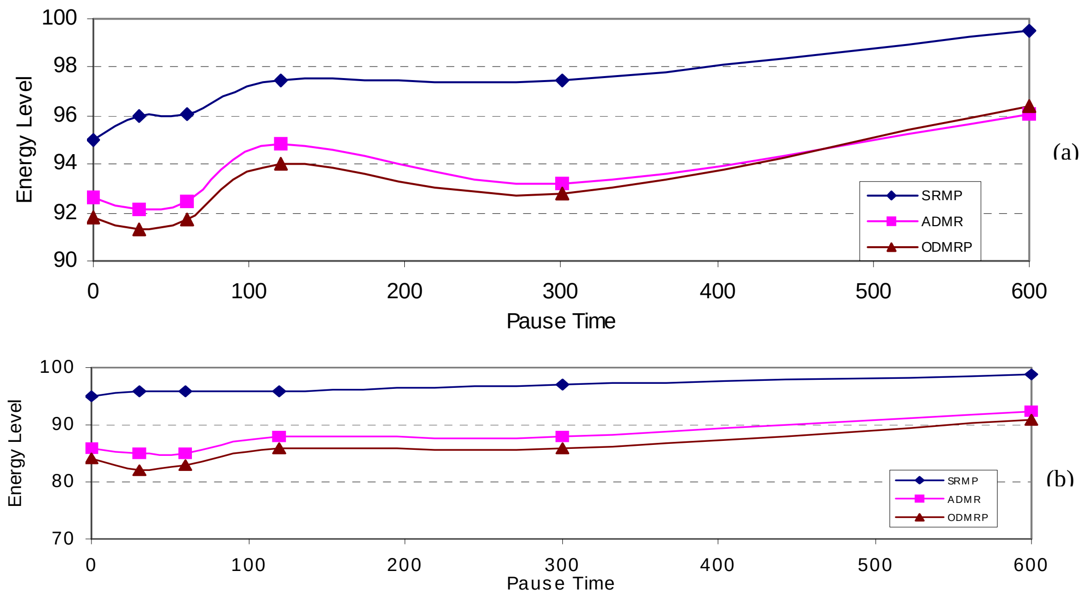


Figure 5.22 Average Energy Level: (a) 1 Multicast Group Case and (b) 3 Multicast Groups Case

Figure 5.22, highlights one of the important features in our protocol, which is its great efficiency in energy consumption. Our encouraging results for SRMP refer to the energy based selection approach; applied during the forwarding nodes selection, at each mesh construction. The obtained results illustrate SRMP minimum consumption compared to ODMRP and ADMR. This behavior takes place for the different multicast group compositions.

The second multicast group case shows a little energy consumption (energy level ≈100). In this case, the number of receivers is small for each multicast source, allowing sparse mesh construction for each multicast group. Each sparse mesh invokes less number of nodes, causing less consumption compared to the first multicast group case. Still quite large number of receivers exist in the first multicast group case, allowing denser mesh construction that consumes more energy.

When the network tends to stable state, the link failures are quite less, which minimizes the energy consumption required for maintenance. ODMRP shows the worst energy consumption due to its continuous flooding approach affecting the power resources at each node. Also, the protocol's maximum overhead consumes more energy with the vast number of the control packets.

We end our comparison study in this section by evaluating the protocol's performance through consulting the MAC layer. In fact, we study the number of re-transmission of data packets at the MAC layer as well as their rate. In Figure 5.23, SRMP data re-transmission size is almost negligible with respect to ODMRP and ADMR, where ODMRP exhibits the worst results for this metric. The connectivity quality, which is the main concept of our proposed protocol SRMP, provides higher connection quality, assuring the maximum availability of each two nodes constituting a link. This availability is studied in terms of the nodes' physical existence, sufficient energy, strong signal quality, and prediction for the period of availability. All these factors together provide qualitative links, which are efficient during transmission. As a result, the MAC layer is not highly charged with huge size of re-transmission compared to the other two protocols.

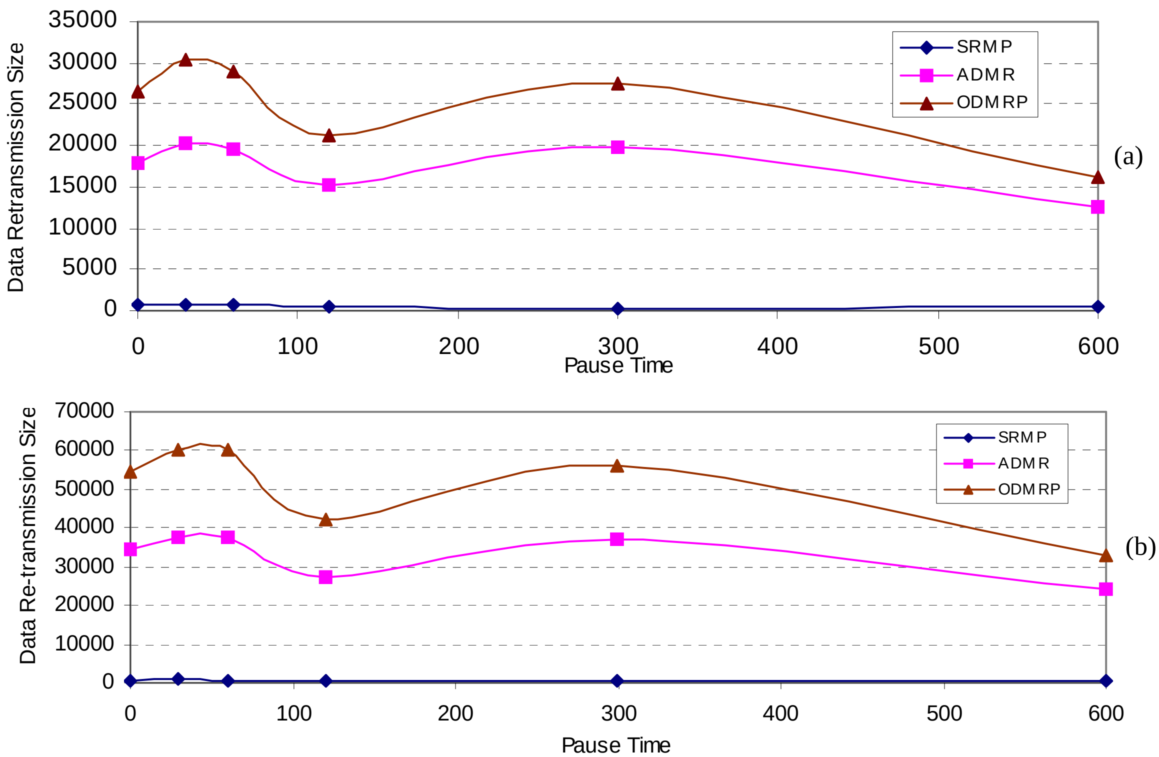


Figure 5.23 Average Data Re-transmission Size: (a) 1 Multicast Group Case and (b) 3 Multicast Groups Case

This evaluation comes in favor of SRMP compared to ODMRP and ADMR. SRMP slight data re-transmission size decreases the network load, allowing efficient utilization of bandwidth and resulting in efficient multicasting. At this point, SRMP behavior conforms very well to the main idea of multicasting, which is efficient utilization of bandwidth. As a mean of measuring the rate of channel utilization due to re-transmission of data, we use the data re-transmission rate metric, see Figure 5.24. We notice that SRMP surpasses ODMRP and ADMR by a huge difference in the first multicast group case and by a large difference in the second multicast group case. SRMP behavior for this metric verifies our previous results concerning SRMP efficient bandwidth utilization.

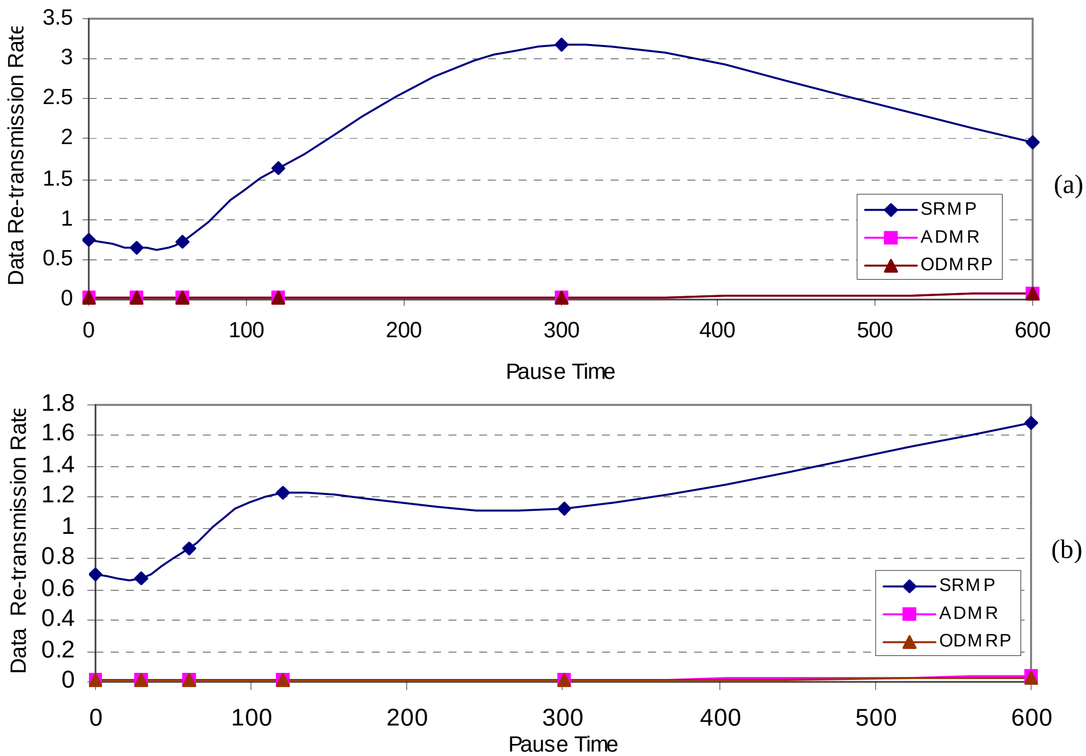


Figure 5.24 Data Re-transmission Rate: (a) 1 Multicast Group Case, (b) 3 Multicast Groups Case

In conclusion, SRMP allows economic use of resources in terms of its energy conserving approach that minimizes the energy consumption at the network equipments (nodes) and hence minimizes the power consumption. Also, SRMP efficient use of bandwidth causes minimized load on the network. Through these features, SRMP fits very well in an ad hoc network environment, and directly conforms to the concept of multicasting. Furthermore, SRMP delivery ratio is strongly encouraging starting from intermediate mobility, and it always exhibits a minimum overhead.

5.6.4 Energy-based Evaluation in a Scalable Network

Our performance analysis, in this section, aims at evaluating SRMP performance in more scalable network and with different multicast groups composition. We study the effect of varying the multicast group composition on the performance. Since SRMP exploits an energy-conserving scheme during the construction of its multicast topology, our focal study and analysis in this section is to accomplish an energy-based performance evaluation. To fulfil this goal, we exploit new performance metrics considering the protocol's efficiency in conserving energy. Our obtained results demonstrate a performance difference with different multicast groups' composition.

5.6.4.1 Simulation Model and Scenarios

We simulated the behavior of a MANET composed of 50 nodes in a 1000 m x 1000 m square area, and operating over 900 seconds of simulation time. Each run of the simulator executes a scenario containing all movement behavior of the ad hoc network nodes, following the RWP mobility model. Each node starts with the same initial energy, which is chosen to be sufficiently large and equal to 50 Joules.

We studied runs with a maximum node movement speed of 10 m/s, using two different pause times implying highly mobile networks states as well as stationary state. A pause time of 300 represents a network in which nodes are moving with a high mobility, while a pause time of 900 represents a network in a stationary state. The multicast traffic sources in our simulation generate constant bit rate (CBR) traffic. Each traffic source originates 64 bytes data packets, using a rate of 4 packets/second.

We used 5 various compositions of multicast groups studying the effect of changing the group composition on SRMP performance. Firstly, we considered 3 cases for one multicast group, consisting of 1 source and 10, 20, and 40 multicast receivers respectively. Through studying these cases, we could observe the difference in performance behavior due to incrementing the number of receivers. Then we considered 2 cases for two multicast groups, consisting of 1 source and 5 and 10 receivers respectively. These last cases are used to explore SRMP performance behavior in an environment consisting of more than one group.

5.6.4.2 Results and Analysis

We evaluate the performance of SRMP studying the effect of changing the multicast group composition on its performance. As a means of providing an energy-based evaluation, we develop two new energy-based performance metrics named the ***average path energy*** and the ***average path energy adequacy***. These metrics are calculated at the multicast source and are defined respectively in Equation 5.2 and 5.3.

$$\textbf{Average path energy} = \frac{\sum_{i=1}^{N} PathEnergy}{N} \qquad (5.3)$$

$$\textbf{Path Energy} = \frac{\sum_{i=1}^{L} NodeEnergyLevel}{L}$$

N: total number of paths stored at the routing cache of the multicast source

L: total number of nodes constituting a path

Average path energy adequacy = $\dfrac{\sum_{i=1}^{N} PathEnergyAdequacy}{N}$ (5.4)

Path Energy Adequacy = $Minimum(NodeEnergyLevel)$

N: total number of paths stored at the routing cache of the multicast source

We measured these metrics at different intervals throughout the whole simulation time. The average path energy implies the protocol's efficiency in energy consumption under different network's load, and the average path energy adequacy indicates the reliability of the nodes running SRMP based on their battery resources. It makes use of the minimum node energy in order to estimate the worst energy case for each route.

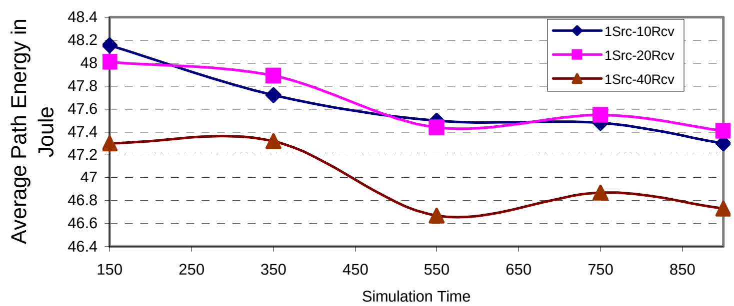


Figure 5.25 1 Multicast Group Cases: Average Path Energy Adequacy

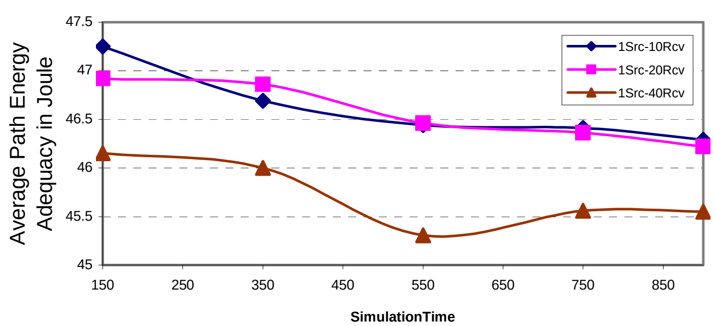


Figure 5.26 1 Multicast Group Cases: Average Path Energy

Figure 5.25 and 5.26 demonstrate respectively the obtained results for the one multicast group cases, considering constant pause time = 300 seconds that implies high mobility. It is noticed that the 10 and 20 receivers' cases exhibit almost a similar behavior, while the 40-receivers case shows the least average path energy and average path energy adequacy. Thus, the considerable increase in the multicast group size from 10 to 40 receivers causes more energy consumption among the available paths on the mesh. Also, the paths adequacy decrease allows the existence of weaker battery power nodes on these paths.

The increase in the multicast group size from 10 to 20 receivers does not show a significant impact on the energy consumption, or on the nodes reliability throughout the whole simulation time. The 20 receivers case shows only a slight increase in the average path energy during the simulation time interval (300,400) and starting from simulation time 600 seconds. Since we consider pause time value equals to 300 seconds, these periods encompass nodes mobility and thus require some mesh reconfigurations. The larger mesh size at the 20-receivers case, compared to the 10-receivers case, requires lesser re-configurations and thus allows lesser consumption. Regarding the average path energy adequacy, the 20 receivers case shows also a slight increase during the simulation time interval (300,400), while it is almost similar to the 10 receivers case starting from simulation time 600 seconds.

A general feature noticed for all the three cases, is the decrease in the average path energy and the average path energy adequacy during the time interval (350,550), where they tend to increase again afterwards. This drop is due to the re-configuration after the nodes mobility, which consumes more energy. The incremental behavior that follows takes place starting from time 600 seconds, which is the expected time for another mesh re-configuration that most probably includes new paths with higher energy levels.

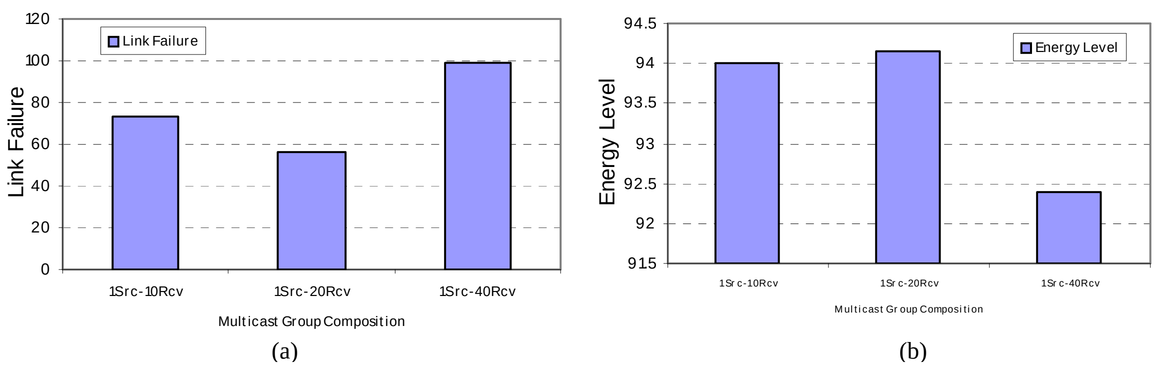


Figure 5.27 Different Multicast Group Composition: (a) Link Failure (b) Energy Level

In Figure 5.27, we study the frequency of link failures and the energy level with respect to the above two metrics, using the same pause time. We observe in Figure 5.27(a) that the 20-receivers case shows the least link failures during the whole simulation, while the maximum obtained link failures is shown at the 40-receivers case. Concerning the energy level in Figure 5.27(b), the 20-receivers case shows the least total energy consumption throughout the whole simulation, while the 40-receivers case shows the maximum energy consumption. The previously obtained results for the average path energy and the average path energy adequacy reflect this behavior for the link failures and the energy level throughout the whole simulation. Actually, the decrease in paths energy allows more consumption and influences the total energy level throughout the whole simulation. The lower the path adequacy increases the probability for link failure occurrence.

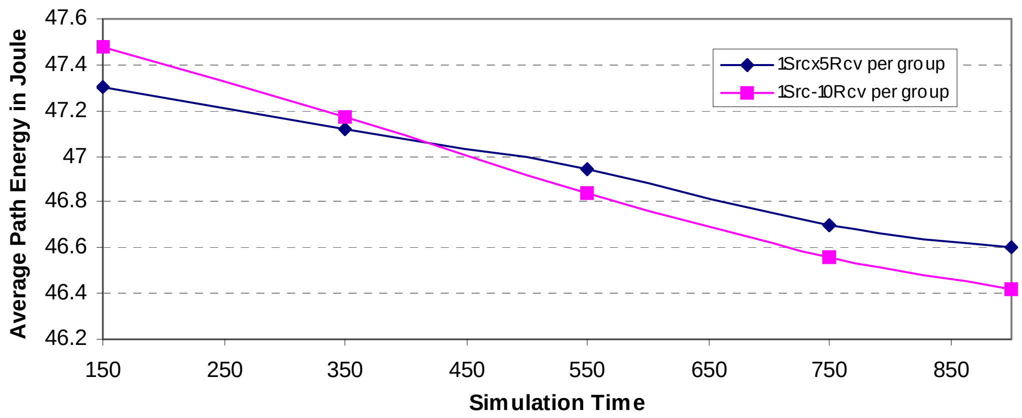


Figure 5.28 2 Multicast Groups Cases: Average Path Energy

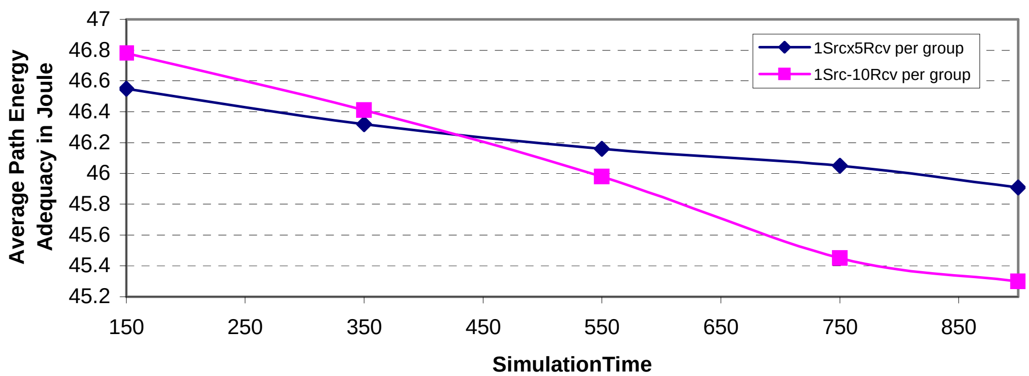
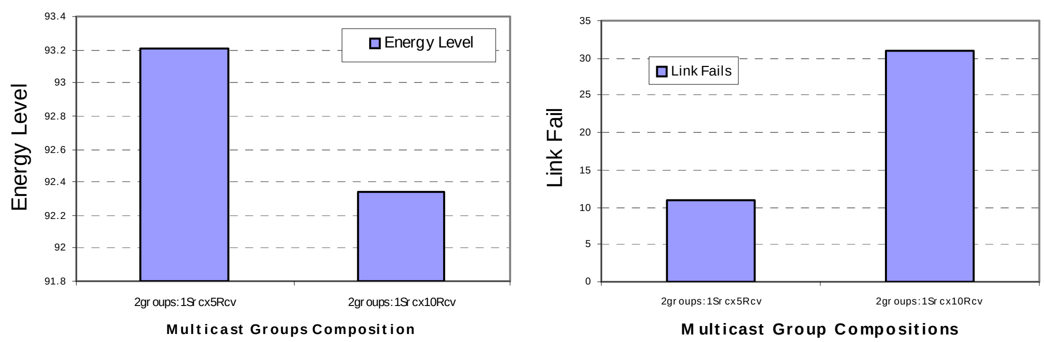


Figure 5.29 2 Multicast Groups Cases: Average Path Energy adequacy

Our obtained results of the average path energy and the average path energy adequacy, for the two multicast group different compositions, are illustrated respectively in Figure 5.28 and 5.29. Here, we considered a pause time = 900 implying stationary state networks. The choice of this pause time is to study the effect of changing the group size on the meshes that are almost static during the whole simulation.

The general behavior noticed in such group compositions, is the gradual decrease in the average path energy and the average path energy adequacy with time. In these cases, the constructed meshes are almost static requiring almost no re-configurations due to the nodes stationary state. Thus the network load is distributed on nearly the same nodes for the whole simulation time, which causes continuous consumption on these nodes translating the gradual decrease in these two performance metrics with time. Concerning the two multicast group different compositions, the 10-receivers multicast groups outperform the 5-receivers groups at the beginning of the simulation. These performance differences is due to the fact that the 10-receivers multicast groups have more intermediate nodes to reply during the routes construction, reducing the size of the reply phase and consuming less energy. While through continuous mesh utilization and data transmission, the 10-receivers multicast groups are exposed to more loads on their meshes to transmit to all the receivers. Thus, a decrease in average path energy and average path energy adequacy is noticed at these cases. We also notice that the average path energy adequacy exhibits larger performance difference. Actually, the 10-receivers multicast groups allow more nodes to be common members in the constructed meshes, which causes more load on these nodes during transmission and makes a more decrease in their energy level.



(a) (b)

Figure 5.30 Different Multicast Groups Composition: (a) Energy Level (b) Link Failure

In Figure 5.30, we study the corresponding link failure and the energy level, using the same pause time. We observe in Figure 5.30(a) that the 10-receivers multicast groups show larger total energy consumption throughout the whole simulation. Also, they show more link failures compared to the 5-receivers multicast groups, see Figure 5.30(b). These obtained results for the average path energy and the average path energy adequacy have an influence on such behavior for the link failures and the energy level. Actually, the decrease in paths energy allows more consumption and influences the total energy level towards the end of the simulation. Similarly, lower path energy adequacy in static meshes state gives no chance for excluding lower energy links and hence increases the link failure size.

In this section, we evaluated the performance of SRMP in an energy-based manner. We studied the protocol's energy consumption in a more scalable network consisting of 50 nodes, and we analyzed the influence of the consumption degree on the reliability of the constructed mesh. Our experiences were run with different multicast group compositions, as a mean of studying the impact of changing the multicast group size on SRMP performance. Throughout our evaluation, we developed two energy-based metrics (average path energy and average path energy adequacy) to study the protocol's power conservation behavior. We carried out our study under different compositions of multicast groups, and from a highly mobile network to an almost stationary network.

Our obtained results in this part show a significant performance difference with the change in the number of multicast groups, as well as with the change in the number of receivers within the same multicast groups number. We generally observed that when the number of receivers considerably increases within a multicast group case, the energy consumption and the battery resource reliability decrease gradually. Moreover, SRMP is more energy conserving when using one multicast group compared to two multicast groups cases, where it has more average path energy, average path energy adequacy, and total energy level. Still, this observation is not satisfied when the increase in the number of receivers within the one multicast group case tends to the total number of nodes in the network. It is also observed that when more than one multicast group are used in a stationary network case, more energy is consumed with larger number of multicast receivers cases causing lower mesh reliability exposed to more link failures.

Concerning the delivery ratio and the end-to-end delay in this scalable configuration, we noticed that SRMP did not show improvements in terms of delay, while it has shown an acceptable delivery ratio. Hence, we conclude that SRMP advantages in scalable configurations concern mainly energy consumption efficiency.

5.6.5 Evaluation with Different Mobility Models

In this section, we present a full performance evaluation and analysis for SRMP under realistic conditions including realistic movements of mobile nodes in the form of different mobility models. We present our simulation results that illustrate the importance of choosing a mobility model in the simulation. We analyze the performance of SRMP using two different mobility models: Random Way Point (RWP) model and Reference Point Group Mobility Model (RPGM) [Cam02, Hon99]. The former provides realistic movements of mobile nodes in ad hoc networks with dynamic and unpredicted nodes' behaviour. The latter is suitable for multicast applications. These models are discussed in details in Chapter 2.

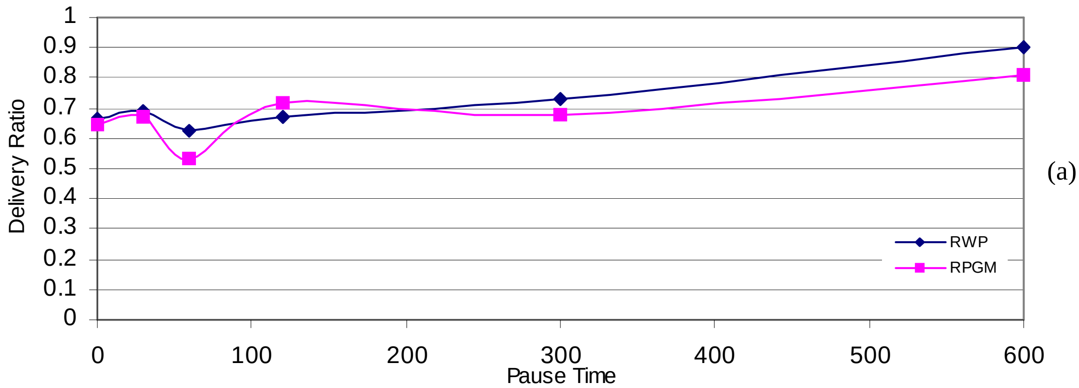
The performance of the proposed protocol SRMP is evaluated through detailed simulation carried out in *ns*-2. The mobility scenarios for the RWP model are generated under *ns*-2, while the RPGM mobility scenarios are generated using Bonn-Motion tool [ics]. We evaluate SRMP performance in terms of *delivery ratio*, *delay*, *control overhead*, and *link failure*. In addition, we use our two proposed comparison metrics, which show the lower battery consumption of SRMP as well as the robustness of its mesh structure.

5.6.5.1 Simulation Model and Scenarios

Our simulations have been run using a MANET composed of 20 nodes moving over a rectangular 1200 m x 300 m space, and operating over 600 seconds of simulation time. In our movement scenario files, nodes move according to the RWP and the RPGM models. Movement is characterized by six different pause times from (0) to (600) along our simulation time. At each pause time, we study several runs with a max nodes movements' speed of 20 m/s. For RPGM mobility scenarios, we have chosen the maximum group size (in terms of number of nodes) to be 4, which is suitable with our network size. The multicast traffic sources in our simulation are constant bit rate (CBR) traffic, point to multi-points traffic type. Each traffic source originates 4 packets per second; each packet is of size 64 bytes. We used 2 different compositions of multicast groups, a first scenario with 1 multicast source and 10 multicast receivers and a second scenario consisting of 3 groups with 1 source and 3 receivers per group.

5.6.5.2 Results and Analysis

SRMP comprises a unique and very important feature throughout dynamic network states, as it provides superlative delivery ratio at very high mobility cases (pause time 0-30). This feature is realized in spite of the mobility model and the multicast group composition; see Figure 5.31. Otherwise, the delivery ratio increases from intermediate to low mobility states. This behavior gives SRMP superiority over other multicast protocols in terms of delivery ratio for highly active networks, and makes it suitable for highly active networks cases. This is due to its robust mesh structure providing quality of connectivity. In highly dynamic networks, the nodes move frequently and require new routes more frequently, allowing frequent re-construction of more stable mesh in terms of higher battery life paths and better links' availability. It is also noticed that the impact of RWP model on the delivery ratio outperforms that of RPGM model in the case of 1 source (1 multicast group) – 10 receivers, and vice-versa in the case of 3 sources (3 multicast groups) – 3 receivers per group. This observation is quite normal since RPGM promotes nodes' movements in groups, which is highly recommended in the case of several multicast group composition. In fact, there is a higher probability for nodes' in RPGM groups to be within the same multicast group, allowing more data packets reception within each group of nodes.



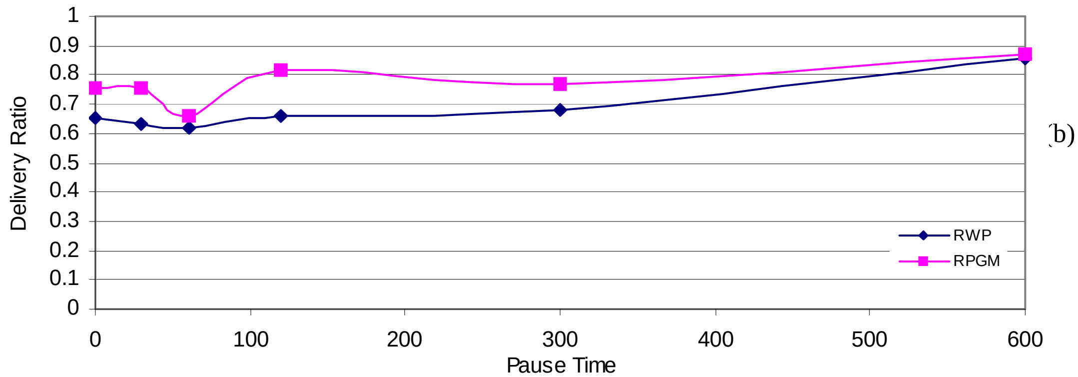


Figure 5.31 Average Delivery Ratio with the Two Mobility Models: (a) 1 Source and 10 Multicast Receivers and (b) 3 Sources and 3 Multicast Receivers per Source

Figure 5.32(a) and 5.32(b) show respectively the average end-to-end delay of data transmission for different multicast group(s) composition. We notice that nearly the same behavior is obtained for the case of 1 source-10 receivers and 3 sources-3 receivers, where the delay decreases with pause time increase as the network tends to stability state. In the 1 source -10 receivers case, RWP has less impact on the delay compared to RPGM for all mobility cases. This is due to the behavior of RPGM model, allowing nodes' movement in groups, each group following a random pattern. In this case, there is a high probability for receivers to follow different movement patterns creating different groups in their movements and hence opposing the 1 multicast group conception. Accordingly, the source requires more delay to reach its receivers. Whereas at the 3 sources-3 receivers case, the two models exhibit nearly the same impact on the delay at intermediate and low mobility due to paths stability, saving the consumed delay to reconstruct meshes. For higher mobility cases (pause time 30-60), RWP has more impact on the delay; this comes as a result of the group movement behavior of RPGM outfitting this type of group composition and hence reducing delay. Another delay feature for this multicast groups composition appears at pause time 0 (hyper active network), where RWP outperforms RPGM in its delay impact. In fact, the frequent mesh re-construction at this network state has a negative impact on RPGM delay. The very short route longevity at this state together with the larger number of nodes sharing the same paths in group mobility, require more delay to re-reach all these nodes.

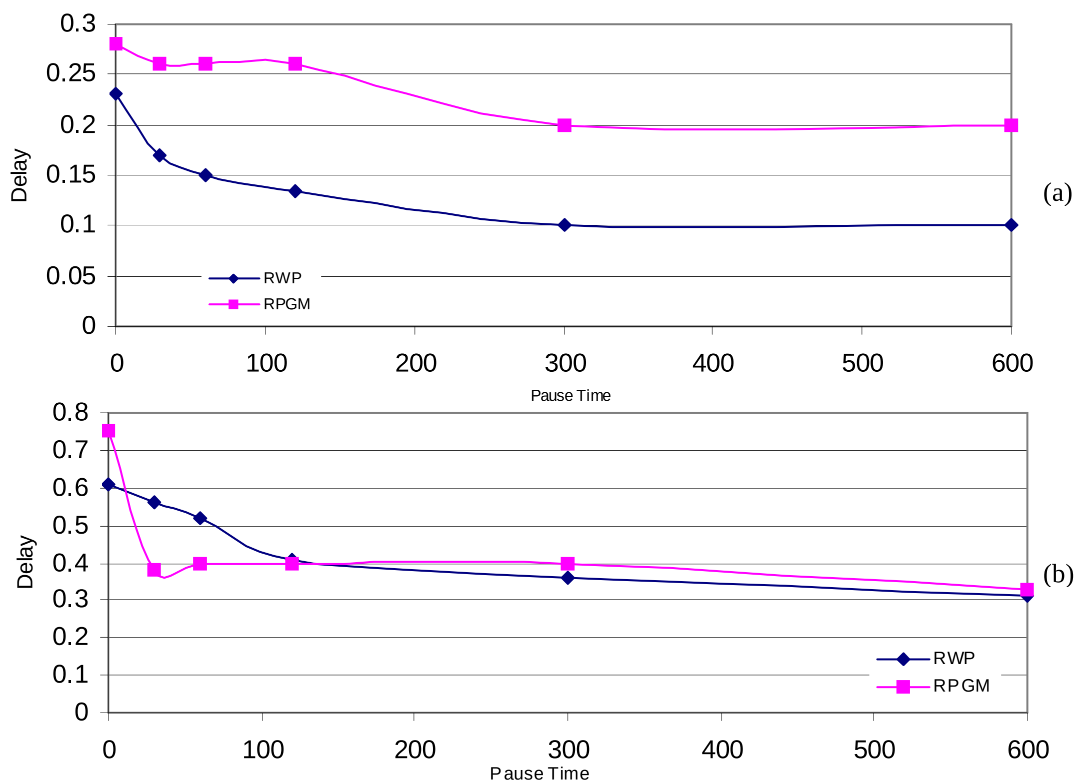


Figure 5.32 Average End-to-End Delay with The Two Mobility Models: (a) 1 Source and 10 Multicast Receivers and (b) 3 Sources and 3 Multicast Receivers per Source

Figure 5.33(a) and 5.33(b) illustrate SRMP control packets overhead for both multicast group(s) composition. Another unique feature in SRMP is its low impact on the control overhead with respect to the traffic load. This feature saves bandwidth and network resources and reinforces SRMP rank as a multicast protocol. This is achieved independent of the mobility model and the multicast group composition. Indeed, SRMP causes fewer overheads thanks to its source routing approach saving the overhead needed to find the next hop. In addition, it exerts no periodic messages, uses the FG concept, which minimizes the flooding scope, and applies simple maintenance mechanisms making use of data transmission with no extra control overhead. We note that RPGM always exhibits fewer overheads compared to RWP as it uses no pause times during its motion pattern and the nodes' movements are not completely random. This feature in RPGM model allows the source to allocate the receivers faster and allows the receivers to construct their mesh towards the source faster, implying less control overhead needed from both sides.

The behavior of SRMP and its adaptation to link failure is shown in Figure 5.34(a) and Figure 5.34(b). We calculated the average link failure to show the robustness of the protocol at different mobility models and multicast group(s) composition. In general, the average link failure rate decreases gradually with pause time increase. As the mobility of nodes increases, the more possibility of links' break takes place.

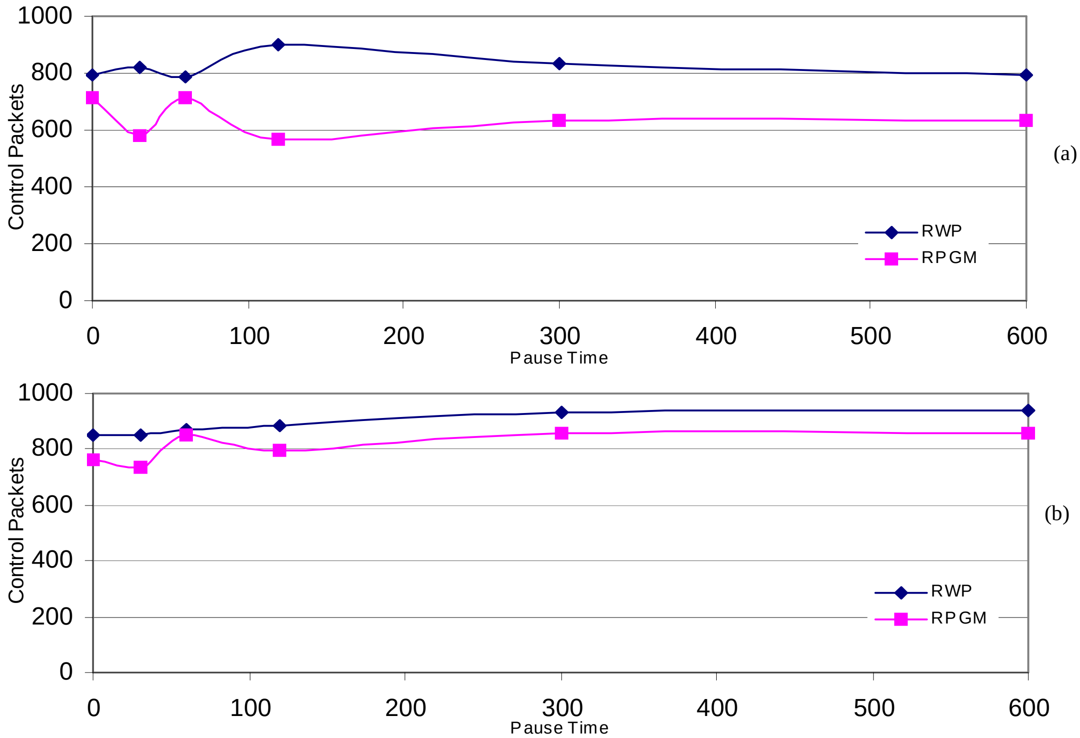


Figure 5.33 Average Control Overhead with the Two Mobility Models: (a) 1 Source and 10 Multicast Receivers and (b) 3 Sources and 3 Multicast Receivers per Source

Concerning the two multicast group(s) composition cases, first case (1 source-10 receivers) has better impact on the average link failure for the two mobility models at intermediate and low mobility cases. This is due to the construction of a denser mesh, constituting of a larger fraction of forwarding group nodes, which provides more robustness and increases the possibility of reaching multicast receivers due to the existence of more possible routes. Comparing the two mobility models behavior, RPGM link failure impact at higher mobility cases surpasses that of RWP. In high mobility, there is a higher probability of providing nodes' movement in neighbor groups. This assures the importance of using RPGM with active networks. On the contrary, RWP shows lower link failures probability at lower mobility cases due to minimizing the randomization rate for each node movement allowing more stable paths thus minimizing the probability of link failure.

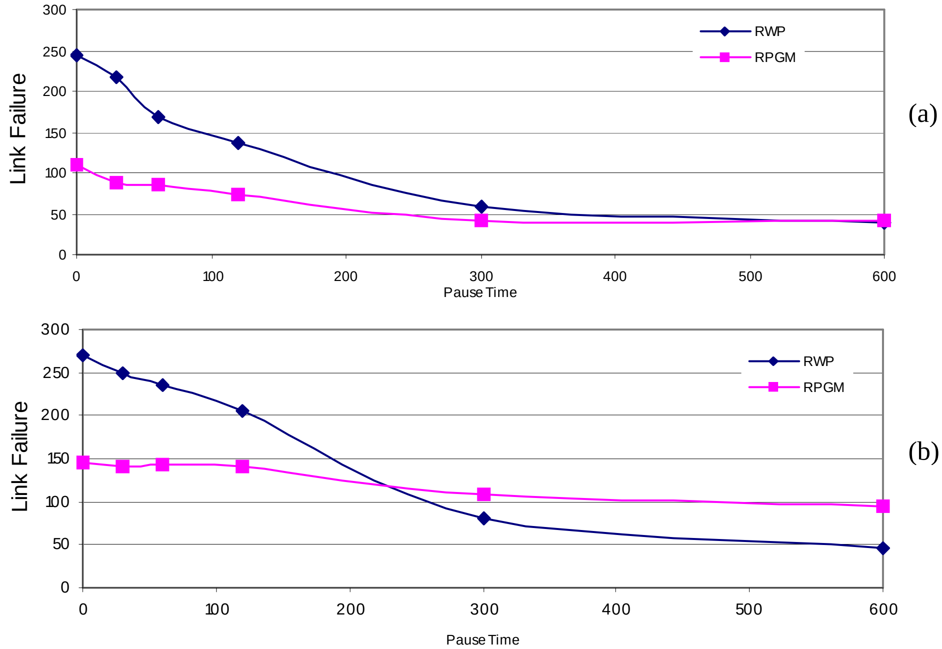


Figure 5.34 Link Failure Rate with the Two Mobility Models: (a) 1 Source and 10 Multicast Receivers and (b) 3 Sources and 3 Multicast Receivers per Source

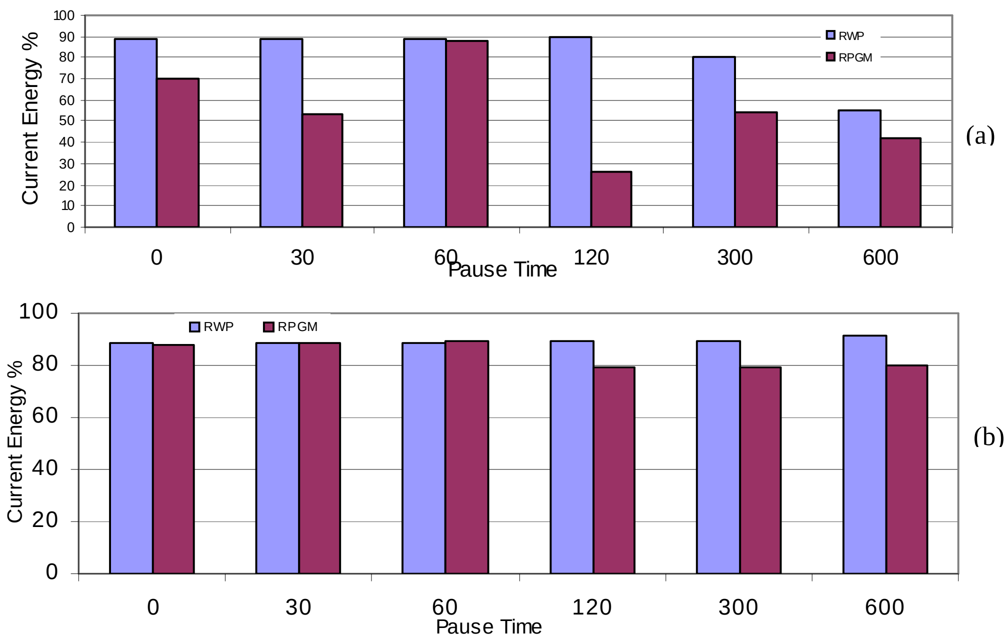


Figure 5.35 Energy Level with the Two Mobility Models (a) 1 Source and 10 Multicast Receivers and (b) 3 Sources and 3 Multicast Receivers per Source

Figure 5.35 illustrates respectively SRMP efficiency in energy consumption for the two cases of multicast group(s) composition. We used an energy level metric in our evaluation; the average energy level for all nodes. It is calculated at the end of the simulation, showing the amount of battery consumed during the simulation. We measured it as a percent of the initial battery energy assuming that all nodes start with the same initial energy. Concerning the two multicast group composition at high and intermediate mobility, RWP exerts the same energy consumption. Still, RWP consumes less energy when the network tends to steady state at the 3 sources –3 receivers case, due to the lower probability of mesh re-construction in this case. Accordingly, lesser energy is consumed at the sparse meshes.

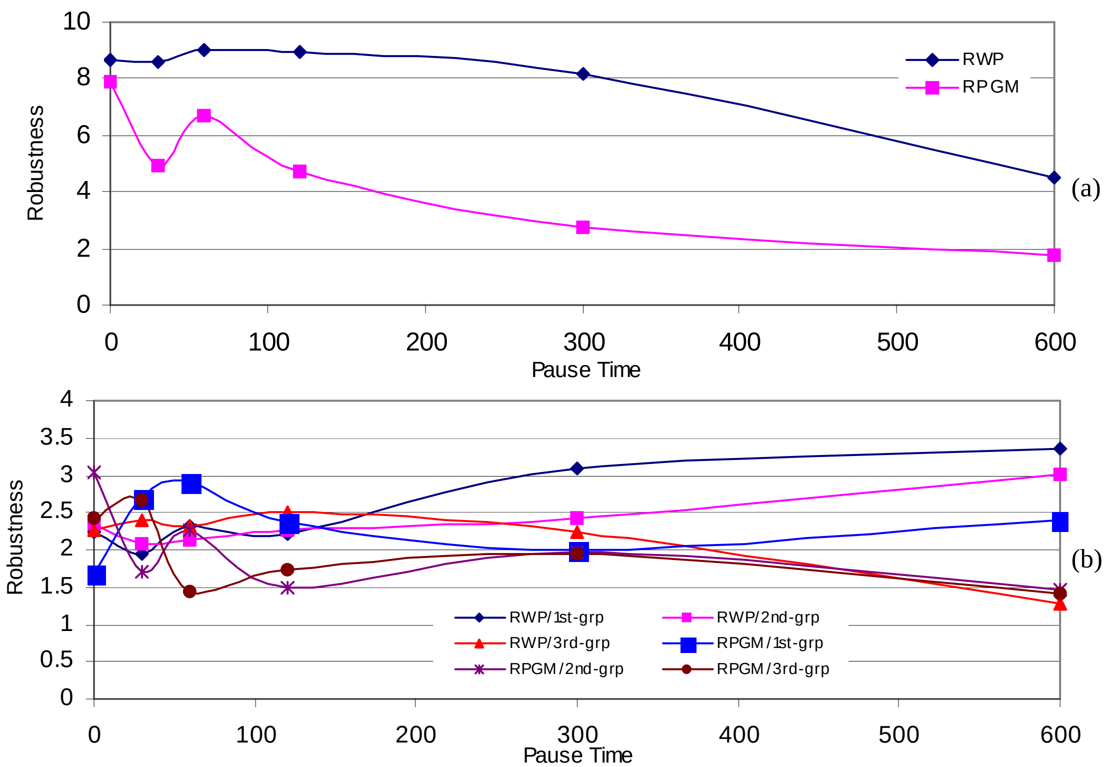


Figure 5.36 Average Nodes Robustness with the Two Mobility Models: (a) 1 Source and 10 Multicast Receivers and (b) 3 Sources and 3 Multicast Receivers per Source

RPGM consumes less energy with different types of mobility at the 3 sources-3 receivers case compared to the one group composition case. This is due to the nodes' movement in groups conforming to more multicast groups composition and giving higher probability for nodes within the same multicast group to share movement patterns. Accordingly, fewer overheads are required to transmit packets implying less energy consumption. Furthermore, the sparse meshes in this case minimize the energy consumption. In general, we notice that the two mobility models consume more energy at lower mobility cases for the 1 source-10 receivers case. A denser and stable mesh is constructed in this case, which allows the transmissions and forwards to frequently use the same stable paths. This causes paths overload and consequently consumes more energy. This feature does not appear at the 3 sources-3 receivers case, since the transmissions and forwards are fairly distributed on 3 different meshes (better traffic distribution). Comparing the two mobility models, RWP shows constantly less energy consumption, due to the high probability of larger number of nodes sharing the same paths for RPGM, causing more energy consumption.

Figure 5.36(a) indicates the average nodes robustness for the 1 source – 10 receivers scenario. We notice the robustness increase with pause time decrease, showing the efficiency of SRMP in maintaining routes towards the multicast receivers thanks to its mesh structure that is continuously updated with the recent stable routes in high mobility cases. The same behavior is nearly achieved for the 3 multicast group scenarios (1 source – 3 receivers for each group), see Figure 5.36(b). The group robustness value is lower compared to the first case due to the small number of receivers compared to the first scenario. Comparing the 3 multicast groups of this scenario, they have nearly the same behavior with different pause times. The slight robustness difference is due to the various composition of each multicast group in terms of time of (Join and Leave) of each multicast receiver.

In highly dynamic network cases (pause time 0-100), best results are obtained for nearly the two mobility models, due to the frequent route discovery following paths' failures. This allows mesh re-construction to select the most recent FG nodes to form stable paths. In addition, RWP model has better impact on robustness in the case of 1-multicast group composition. Here, RPGM exerts smaller mesh size (in terms of number of routes), due to its non-conformity with the 1 multicast group case. As a result, RWP show an enhanced robustness. This feature starts to disappear in the 3-multicast groups case, as RPGM begins to conform to the multiple groups that exist.

5.7 Summary and Conclusion

In this chapter, we proposed SRMP as a mesh-based multicast routing protocol aiming to present an alternative to the existing multicast routing strategies. SRMP follows a reactive approach saving network resources and routing load, and it guarantees fewer overheads in maintaining next hop information by applying the source route concept. Thanks to its selection criteria in mesh construction, stable paths with future links availability and higher battery life are provided. This assures connectivity quality, minimizing the possibility of links' failure together with the overhead needed to re-construct the paths.

Aiming to justify our proposition and investigate its performance, we fulfilled a vast performance evaluation approach in which a variety of mobility and communication scenarios are invoked. We used various network sizes and configurations, several mobility models, different multicast groups' composition. To grade SRMP with respect to the other multicast protocol, we carried out a performance comparison study comparing the performance of SRMP with that of ODMRP and ADMR. We demonstrated that even though the three protocols share similar on-demand behavior, the difference in each protocol strategy leads to performance differential. We also demonstrated that even though SRMP and ODMRP share the mesh-based category, their different mechanisms lead to different behavior and performance results.

Our obtained results, for different network sizes, highlight some remarkable features in favor of SRMP. SRMP mainly tackles two important issues that should be addressed in a suitable multicast routing protocol in an ad hoc network. It shows a significant decrease in control overhead, and it is more efficient in terms of energy consumption. This takes place for all network configurations, traffic types, and multicast group compositions.

SRMP delivery ratio outperforms ODMRP and ADMR when the network tends to be stationary in 20-node network; this is due to its connectivity quality approach creating links that better react to interference and distortion in such stable conditions. Also, it shows an enhanced delivery ratio starting from intermediate mobility, in 30-node network. In this case, SRMP delivery ratio nearly reaches 100% with one multicast group composition. In general, SRMP does not show a delivery ratio enhancement in highly dynamic network due to the full or partial flooding mechanisms in ODMRP and ADMR at the expense of bandwidth utilization. Nevertheless, its delivery ratio constitutes about 75%-80% from the maximum delivery ratio obtained by ODMRP and ADMR.

We observed that SRMP does not show lower delay compared to ODMRP and ADMR. This is due to the application of the selection criteria during the mesh construction and maintenance, causing delay increase. However, it shows an interesting delay decrement with mobility decrease in 20-node network while it shows constant delay behavior starting from intermediate mobility in 30-node network.

Moreover, in 20-node network SRMP shows a link failure decrease with mobility decrease for different multicast group compositions. This is more shown with lower number of multicast groups. Concerning robustness, it is richer at higher mobility cases due to the continuous construction of more stable meshes.

SRMP provides connectivity quality on its constructed mesh, resulting in a negligible size of data packets re-transmission at the MAC layer compared to ADMR and ODMRP. This feature demonstrates SRMP efficiency in bandwidth utilization, which is a necessary requirement for an efficient multicast routing protocol.

Since mobile nodes are thin clients that operate under certain power constraints, energy conservation is an important issue in MANET that is highly considered in efficient routing protocols. As SRMP invokes an energy-conserving scheme during its mesh construction, we aimed to investigate its performance via employing an energy-based evaluation in Section 5.6.4. We carried out our analysis in a more scalable network configuration, to study the battery power reliability of the SRMP nodes. Our obtained results showed a significant performance difference with the change in the multicast group composition, as well as with the change in the multicast group size. We also noted the energy consumption influence on the links lifetime and consequently on the mesh reliability.

In Section 5.6.5, we evaluated the performance of SRMP under realistic conditions, employing more realistic movements of mobile nodes. Beside the random mobility for modeling the mobile nodes movement, we used the group mobility studying its impact on multicast routing. Our obtained results show the impact of changing the mobility models on SRMP performance. Otherwise, SRMP shows two unique features, in such network configuration, in spite of the used mobility model and the group composition: it provides superlative delivery ratio at highly dynamic network's states, and it has a low impact on the control overhead. This saves bandwidth and network load, reinforcing SRMP rank as a multicast protocol. We also observed from our study that group mobility in nodes movement conforms better to more multicast groups.

Due to the difficulty of the mixed metrics approach applied in SRMP, we undertake in the next chapter an adaptive study for the thresholds of the four selection metrics introduced in Section 5.3. Our goal is to recommend appropriate thresholds set according to the network configuration.

CHAPTER 6 STUDYING THE THRESHOLDS' EFFECT ON SRMP PERFORMANCE

The SRMP mesh establishment is achieved via invoking the concept of connectivity quality through four selection criteria for the choice of each link. Such criteria consider the stability of each node's pair constituting the link, the quality of the signal transmitted on the link, and the availability of the link. In this chapter, we investigate the appropriate choice for the selection metrics values during the mesh construction. The goal is to provide reliable transmission upon the mesh structure.

6.1 Motivation

Recall from Chapter 5, we apply selection criteria for each link setup during SRMP operation, making use of four selection metrics: *association stability*, *signal strength*, *link availability* and *battery level*. We introduce four thresholds values for these selection metrics: *association_stability_threshold*, *signal_strength_threshold*, *link_availability_threshold* and *energy_level_threshold*. The set of threshold values indicates whether the link between each node's pair should be included in the routing process or not. For reliable and efficient transmission, the choice of the appropriate thresholds' values should provide efficient routes, in terms of the maximum multicast receivers coverage together with the minimum possible resources consumption.

Consequently, we study in this chapter the thresholds' effect on the performance of SRMP. We study and analyze our protocol's behavior under several combinations of thresholds' values. Our goal is to extract an appropriate threshold set that could provide the construction of a robust mesh, and hence resulting in a better performance for our protocol.

6.2 Analysis Approach and Test Cases

We applied a simulation-based analysis, where various combinations of thresholds' values are invoked through the use of twelve test cases. We analyzed our protocol's performance for each test case as a mean of studying the thresholds' effect as well as finding the appropriate thresholds set.

For simplicity, we carried out our analysis on a small network configuration consisting of 20 nodes located in a rectangular topography 1200 meter x 300 meter. The radio range is constant for each node and is equal to 250 meter. In addition, we used constant initial energy for each node equal to 50 Joules. Our experiences were run for a simulation period equals to 600 seconds, where we chose a multicast group composition constituting only of one group with 1 multicast source and 10 multicast receivers.

We based our analysis and study on six performance metrics: *delivery ratio*, *end-to-end delay*, *control overhead sent*, *link failure*, *robustness* and *energy level*.

We used 12 combinations of different values for the *association_stability_threshold* and the *link_availability_threshold* (see Table 6.1). The *signal_strength_threshold* takes a fixed value equals to *constant_value* x *reception_sensitivity*. The *reception_senstivity* in our simulation is the acceptable received signal power that assures correct reception, it is calculated as a function of the distance between the nodes (each node is aware of its distance to each of its neighbors), the radio range, and the radio propagation model.

Since the battery depletion is a function of time and processing size, then the battery energy decrease with time. Accordingly, we calculate the *energy_level_threshold* as a function of time, through dividing our 600 seconds simulation period into three intervals and we fix a value for the *energy_level_threshold* at each interval, this is illustrated in Figure 6.1. As mentioned previously, we start with a large initial energy (50 joules) for each node to allow sufficiently high energy resource at the beginning.

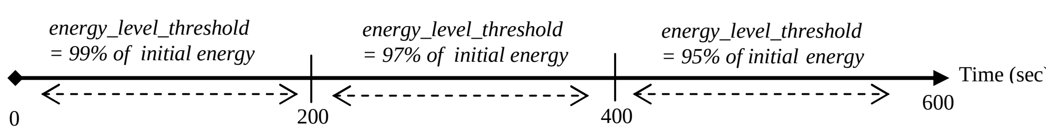


Figure 6.1 Value of the energy_level_threshold at Different Intervals

The choice of the *association_stability_threshold* values considers different cases, from good associated node's pair to highly associated node's pair. The choice of the *link_availability_threshold* values is made based on the prediction-based link availability model derived in [Jia01]. As mentioned previously, this model assumes mobility epochs for nodes' movements, where an epoch is a random length interval during which a node moves in a constant direction and speed. The link availability, [$\mathbf{L}(\mathbf{T_p})$], can be predicted making use of Equation 5.2.

Table 6.1 SRMP Thresholds' values for the 12 different test cases

Test Case	*association_stability_threshold*	*link_availability_threshold*
1	5	0.78
2	5	0.79
3	5	0.8
4	6	0.78
5	6	0.79
6	6	0.8
7	7	0.78
8	7	0.79
9	7	0.8
10	8	0.78
11	8	0.79
12	8	0.8

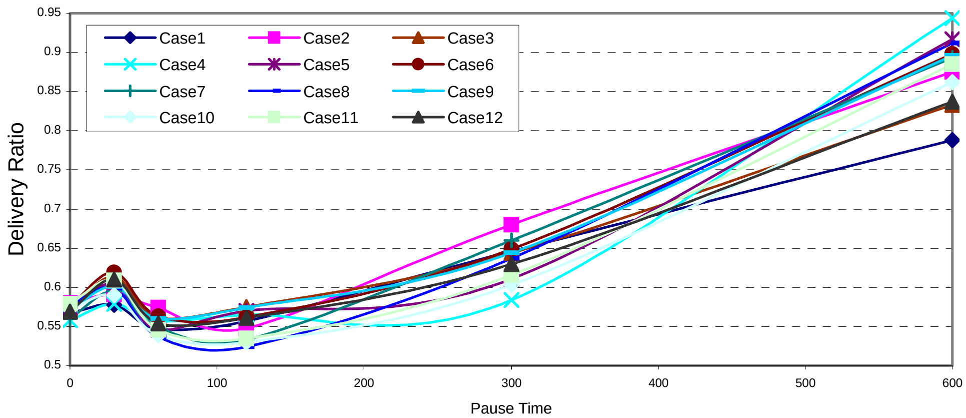
We chose the value of T_P between 20 and 25 seconds, which is a suitable value compared to our whole simulation time. And we chose the value of λ^{-1} to be equal to 60 seconds. Through appropriate substitutions in Equation 5.2, we can get the possible values for the predicted link availability. Accordingly, the choice of the *link_availability_threshold* values is made to be respectively equal to 0.78, 0.79 and 0.8. By this, we can include fair to high link availability cases.

The following sections analyze and study the performance behavior of our routing protocol SRMP with the 12 different test cases. This is carried out through analyzing the thresholds' impact on our previously mentioned 6 performance metrics.

6.2.1 SRMP Delivery Ratio

Figure 6.2 shows the SRMP delivery ratio with the different test cases. Nearly the same behavior is achieved for all the test cases, where the delivery ratio tends to increase linearly starting from intermediate mobility (pause time 250-300). While at high mobility cases, it is obvious that there is a peak increase at pause time 30 providing the maximum delivery ratio for high mobility cases at this pause time. In general, the mesh re-construction is more frequent at high mobility cases, allowing the construction of more recent stable paths. At pause time 0 (hyper mobile network), the lifetime of the mesh is very short, while the lifetime increases as the pause time tends to 30 and hence allowing the peak increase in delivery ratio. Then a little drop in delivery ratio is noticed at pause time 60, returning to the lower frequency of mesh re-constructions at this pause time although the mobility is still high. At this state most of the constructed paths are lost, while a sparse mesh still exists, thus preventing a new mesh re-construction and causing this drop in delivery ratio.

In some test cases, we notice a delivery ratio decrease from pause time 60 to pause time 120. More precisely, this behavior takes place at test cases (2, 7, 8, 10, and 11). The lower *link_availability_threshold* value of these five cases, compared to the other test cases, causes the decrease in delivery ratio even at higher *association_stability_threshold* values. Thus, the *link_availability_threshold* has more impact on the delivery ratio compared to the *association_stability_threshold*. This behavior appears at pause time interval [60,120] due to the lower frequency of mesh re-constructions in this case, and the dependence on a sparse mesh that lacks in total the paths' availability



. Figure 6.2 Delivery Ratio

In Figure 6.3, we study the thresholds' effect for highly active network states (pause time 0 and 30) and for network tending to steady state (pause time 300 and 600). Figure 6.3(a), shows the delivery ratio behavior for the different test cases at pause time 0 (highly active network). SRMP has a constant delivery ratio with nearly all the test cases, excluding test cases (1, 4, and 7), where the delivery ratio is a little bit low. In fact, in these three test cases the *link_availability_threshold* has its minimum value and thus showing its impact on the delivery ratio in this highly dynamic network. In spite of the minimum value of the *link_availability_threshold* at test case 10, this behavior does not take place due to the maximum value of the *association_stability_threshold* in this case, hence compensating the weak link availability during the choice of the highly stable paths.

At pause time 30 (Figure 6.3(b)) the delivery ratio has nearly the same behavior as the above case, except that a delivery ratio increase is shown at test cases (3, 6, 7, and 12). The *link_availability_threshold* has its maximum value in these test cases, and thus provides more robust delivery at this less dynamic network state, compared to pause time 0.

Concerning the nearly static (pause time 300) and static (pause time 600) network states, it is noticed in Figure 6.3(c) that the delivery ratio comprises an increase at test case 2 as well as at test cases 5 up to 9, while it starts to decrease from test case 10. Actually, the first test cases show almost high values for the *link_availability_threshold* while the *association_stability_threshold* is almost high. Thus robust delivery is provided allowing higher delivery ratio at this nearly static network. On the contrarily, starting from test case 10 both thresholds values are high which allows the construction of a small size mesh, consisting of robust paths. Consequently, this mesh does not cover all the multicast receivers, which translates the delivery ratio behavior.

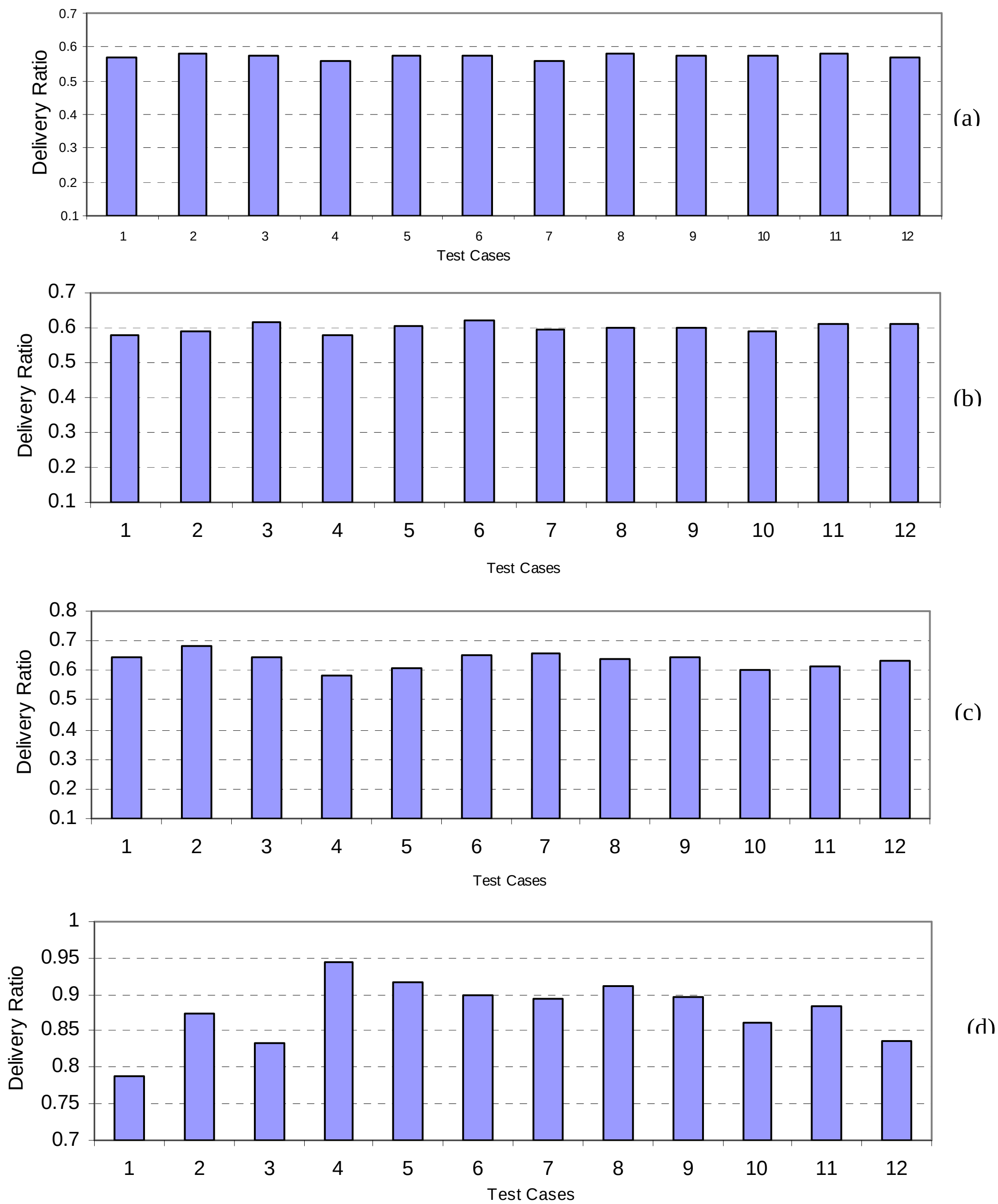


Figure 6.3 Delivery Ratio for Different Test Cases: Highly Mobile and Stable Network States, (a) Pause Time 0, (b) Pause Time 30, (c) Pause Time 300 and (d) Pause Time 600

A similar behavior takes place at pause time 600 where the network is completely static, see Figure 6.3(d). The only difference emerges at test case 4 showing an increase in delivery ratio. In spite of the *association_stability_threshold* value, which is a little bit small, and the small value of the *link_availability_threshold*, the delivery ratio increases due to the network complete stability at this pause time. Actually, the network stable state minimizes the correlation and interference resulting from the nodes' movements, such that longer lifetime links are provided.

We conclude that the *link_availability_threshold* value has the highest impact on the delivery ratio for nearly all mobility types, while the impact of the *association_stability_threshold* value starts to appear at static network cases.

6.2.2 SRMP End-to-End Delay

In Figure 6.4, we analyze the thresholds' impact on the end-to-end delay illustrating our results for the 12 test cases. A general observation is the delay drop for all the test cases at pause time 30. This is due to the peak increase in delivery ratio at this pause time (see Figure 6.2). Otherwise, the delay tends to decrease at pause time interval [60, 200] as the network tends to be more stable for nearly all the test cases. Also we notice for nearly all the test cases the delay increase from intermediate to low mobility cases, excluding test cases (5 and 10). The reason for this delay increase in more stable network, is the larger size of the constructed mesh at these cases, in terms of more paths, and thus more data flooding takes place on this mesh causing more delay in order to provide a complete transmission.

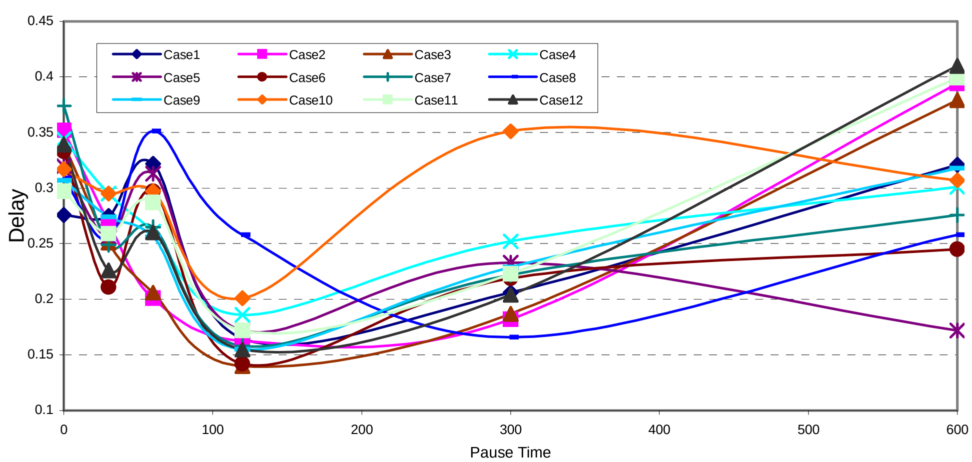


Figure 6.4 End-to-End Delay

The delay drop at test case 5 is due to the relative high value of the *link_availability_threshold* compared to the intermediate value of the *association_stability_threshold* at this case. This minimizes the size of the constructed mesh in terms of number of paths, and hence decreases the delay during the transmission on this mesh. Test case 10 comprises a maximum value for the *association_stability_threshold* assuming highly attached nodes. This allows the construction of high quality paths allowing lesser mesh size, and thus giving the same previous behavior as test case 5.

Figure 6.5 illustrates the thresholds' effect on the end-to-end delay at highly dynamic and steady state network cases. At pause time 0 (Figure 6.5(a)), we notice that the maximum delay is shown at test cases 7 and 12. Actually, the *association_stability_threshold* is considerably high at these two cases of highly dynamic network where the nodes are less associated, while the *link_availability_threshold* is high at test case 12. As a result, a quite sparse short-lived mesh is constructed leading to more delay in transmission, frequent re-construction, and re-transmission.

On the other hand, test case 1 shows the minimum delay due to the satisfactory values for both thresholds at this case in the context of a highly dynamic network. This causes the construction of a less sparse mesh with longer lifetime, and thus allows less delay compared to the previous two test cases. Otherwise, we notice that the delay has nearly the same behavior for nearly all the other test cases.

At pause time 30 (high but not continuously dynamic network) (Figure 6.5(b)) the maximum delay is shown in test cases 4 and 10, while the minimum delay is shown in test cases 6 and 12. In test cases 4 and 10, the *link_availability_threshold* value allows the construction of a denser mesh with lesser links' lifetime. As a result, more data flooding takes place along this mesh that does not necessarily cover all the multicast receivers, thus more delay arises during data re-transmission and paths re-construction. In test cases 6 and 12, the *link_availability_threshold* value allows only long lived paths to be constructed. This is suitable in such high dynamic network and results in smaller and more stable mesh. Lower delay is introduced by this mesh, due to the lower frequency of re-construction and re-transmission.

At pause time 300 in Figure 6.5(c), when the network tends to steady state, the minimum delay is shown at test case 8 while the maximum delay is shown in test case 10. In the former, both thresholds values allow a mesh construction among highly associated node's pairs constituting of highly available links. This saves the delay needed for the re-discovery and maintenance. The latter shows the maximum delay since it comprises the densest mesh at this pause time. This mesh characteristic is due to the satisfaction of both thresholds values on a large number of node's pair, and it increases the data flooding size and causes more delay.

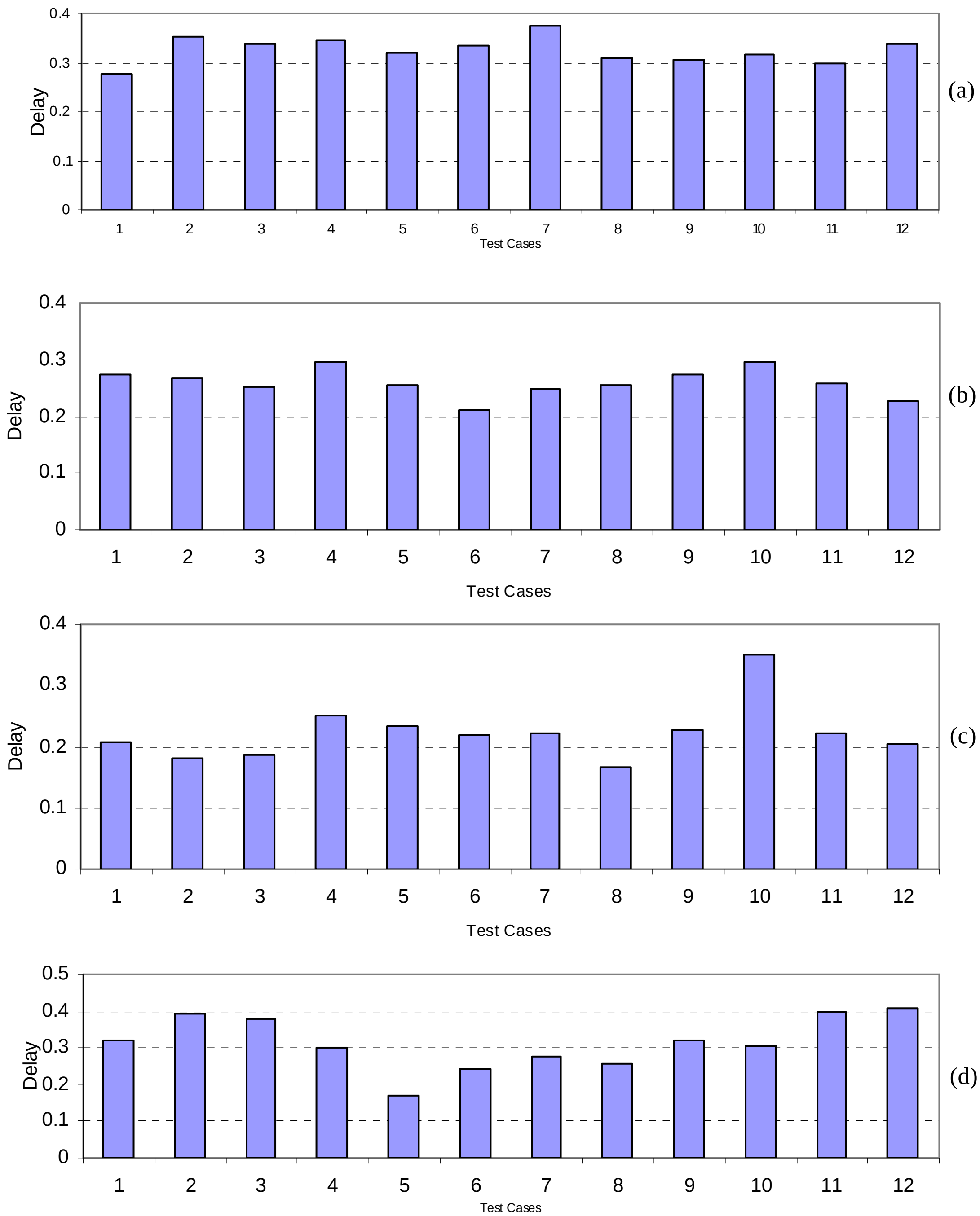


Figure 6.5 End-to-End Delay: (a) Pause Time 0, (b) Pause Time 30, (c) Pause Time 300 and (d) Pause Time 600

The previous behavior changes at completely stable network state (pause time 600), see Figure 6.5(d). The minimum delay is shown in test case 5 due to the moderate thresholds values allowing the construction of almost stable and moderate size mesh. Test cases 2, 3, 11, and 12 show a delay increase compared to the other test cases. The thresholds values in these test cases indicate high links availability and high association between node's pair in test cases (11 and 12). The received signal power, in these cases, fits well to the *signal_strength_threshold*, increasing the mesh density. Consequently, more delay is required for transmission on more number of links even if they do not cover all the multicast receivers.

We observed that the end-to-end delay is more affected by the *association_stability_threshold* value for highly dynamic network state, while it is highly affected by the *link_availability_threshold* value at less dynamic network. When the network tends to steady state we note that both thresholds have similar impact on the delay.

6.2.3 SRMP Control Overhead Sent

Figure 6.6 illustrates the thresholds' impact on the SRMP control overhead in terms of control packets. In nearly all the test cases, a decrease in the control packets sent is noticed at pause time 30. This behavior is due to the more reliable mesh at this pause time providing higher delivery ratio, as previously shown in Figure 6.2. As a result, the control packets sent due to frequent link breaks and maintenance are minimized. Test case 9 does not conform to this behavior, as both thresholds values are extremely high for such a highly dynamic network state, thus more overhead is invoked in re-discovery and maintenance.

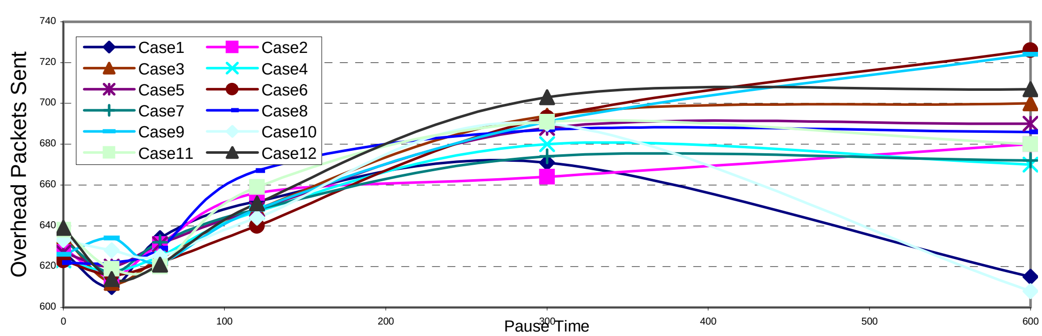


Figure 6.6 SRMP Control Overhead

Otherwise, the control overhead increases with mobility decrease due to the longer life or nearly stable mesh at low mobility cases. This allows more route reply packets to be sent by each multicast receiver during maintenance and mesh refreshment process. Test cases 1 and 10 do not show this behavior due to the lower number of the covered receivers in test case 1 causing minimized delivery ratio, see Figure 6.2, and thus minimizing the overhead sent by the receivers for maintenance. Test case 10 shows a smallest mesh size in terms of the number of the constructed routes, see Figure 6.11(d), which results in less control overhead sent.

At pause time 0, see Figure 6.7(a), we notice an overhead increase as the *link_availability_threshold* value increases. This behavior takes place for the minimum and maximum *association_stability_threshold* values, such that the peak overhead is respectively shown at test cases 12 and 3. Actually, test case 12 allows a larger mesh lifetime compared to the other test cases, at this highly dynamic network state, where the more stable and available paths are chosen. This results in more overheads due to more route reply packets from the receivers for maintenance. In addition, more link breaks appear, see Figure 6.9(a), although the mesh still exists. On the other hand, test case 3 allows larger size mesh constituting of less stable paths, this results in more link breaks increasing the overhead due to re-discovery and error packets.

A different behavior is shown for the less dynamic network case (pause time 30), see Figure 6.7(b). As noticed, the overhead packets decrease as the *link_availability_threshold* value tends to its maximum. This behavior takes place for each *association_stability_threshold* value. This refers to the more stability of the constructed mesh allowing less links breaks. Test case 9 does not conform to this behavior, where highly available links are constructed between less associated node's pairs due to both thresholds values. Thus it shows the peak overhead resulting from more link failures. Figure 6.9(b), verifies the link failure behavior for the discussed test cases.

Figure 6.7(c), demonstrates the overhead at pause time 300 (nearly stable network). The general behavior is the overhead increase for each *association_stability_threshold* value with the increase in *link_availability_threshold*. We notice more increase at the maximum value of the *association_stability_threshold*. This is due to the more stable mesh construction allowing more overheads due to route reply packets sent by receivers for maintenance. The same behavior is shown at pause time 600 (static network), Figure 6.7(d). The only difference is that test cases 1 and 10 show the minimum overhead, as discussed previously in Figure 6.6.

We conclude that the control overhead is highly affected by the *link_availability_threshold* value at high mobility cases. However, when the network tends to be stationary, both thresholds have similar impact on the control overhead.

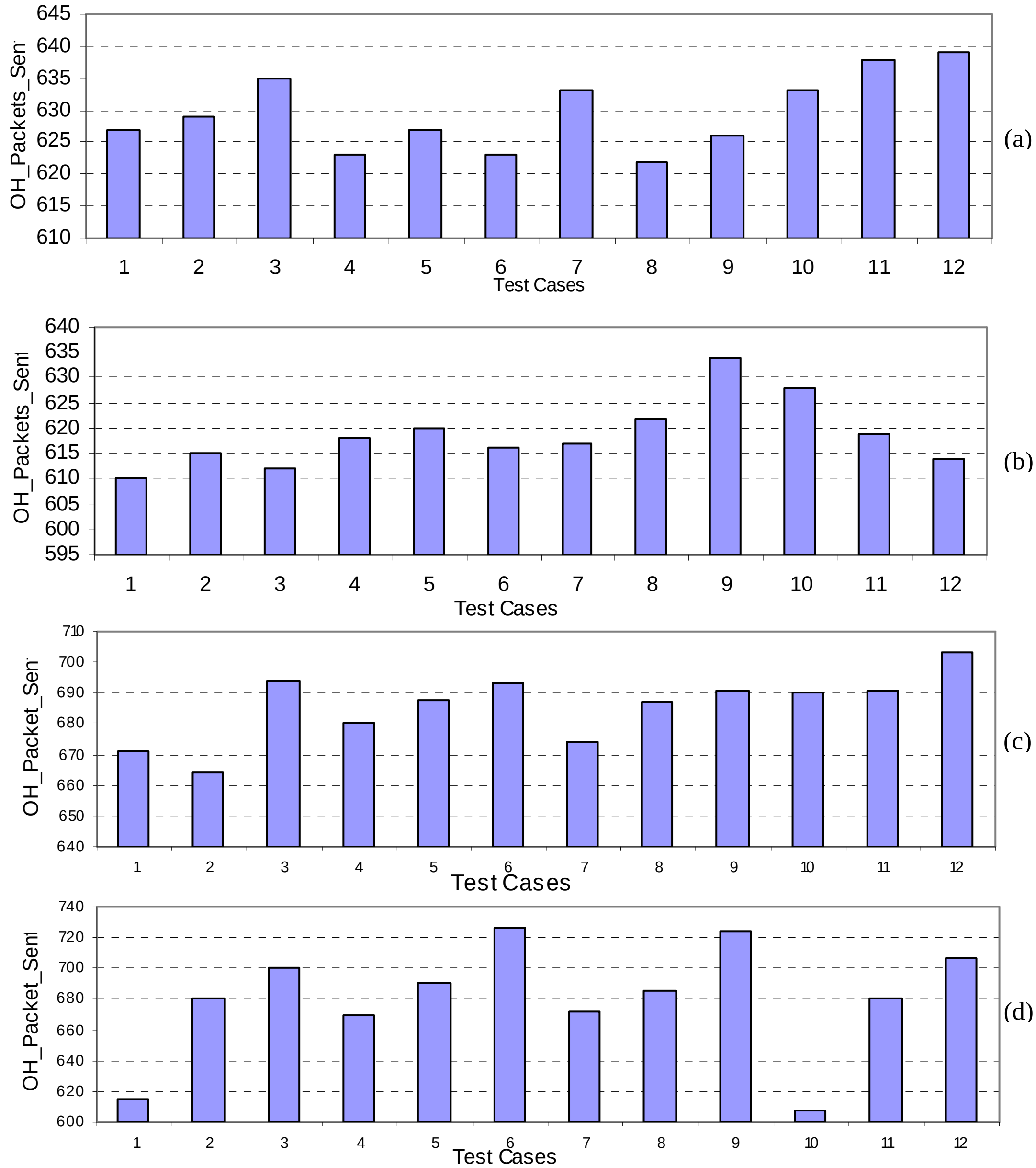


Figure 6.7 Control Overhead: (a) Pause Time 0, (b) Pause Time 30, (c) Pause Time 300 and (d) Pause Time 600

6.2.4 SRMP Link Failure

In Figure 6.8, we analyze the link failure from highly dynamic to stable network states. The general behavior noticed is the link failure decrease with mobility decrease, until reaching the minimum link failure at static network (pause time 600). This behavior takes place in all the test cases, and returns to the more possibility of link failures with more mobility and in more dynamic network states.

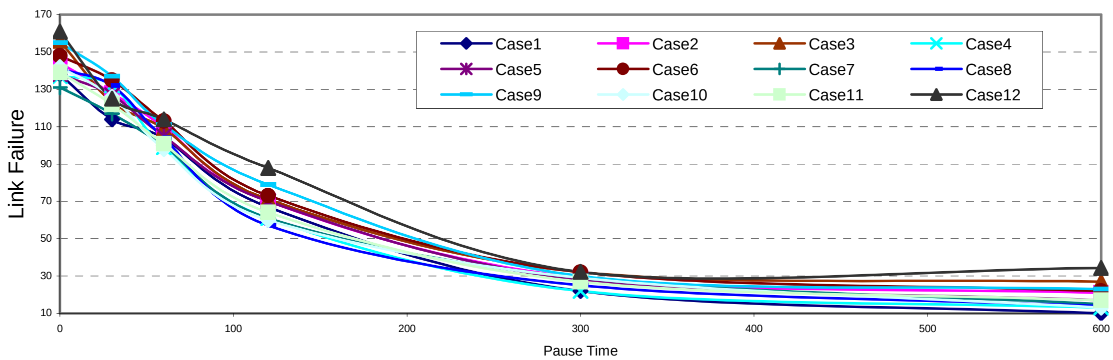


Figure 6.8 Link Failure

In Figure 6.9, we notice that the general behavior for highly dynamic network state (pause time 0 and pause time 30) is the link failure increase with the increase in the *link_availability_threshold* value, see Figure 6.9(a) and 6.9(b). This behavior takes place for each value of the *association_stability_threshold* at pause time 0 and for lower values of the *association_stability_threshold* at pause time 30. In general, this is due to the longer lifetime of the mesh as the *link_availability_threshold* value increases, thus allowing more chances for more link breaks to occur with different nodes mobilities while the mesh is still alive. At pause time 30, this behavior is clearer for smaller values of the *association_stability_threshold*. At this less dynamic network state, the constructed mesh is less stable for lower values of the *association_stability_threshold* and thus the link failure is more liable.

In Figure 6.9(c) and 6.9(d), nearly the same link failure behavior takes place where the peak link failure is shown in test case 12 due to the higher mesh lifetime. On the other hand, the minimum link failure is shown in test case 1. As both thresholds values are minimum in this test case, a denser mesh (constituting of more links) is constructed, and thus fair traffic distribution is provided on the different paths.

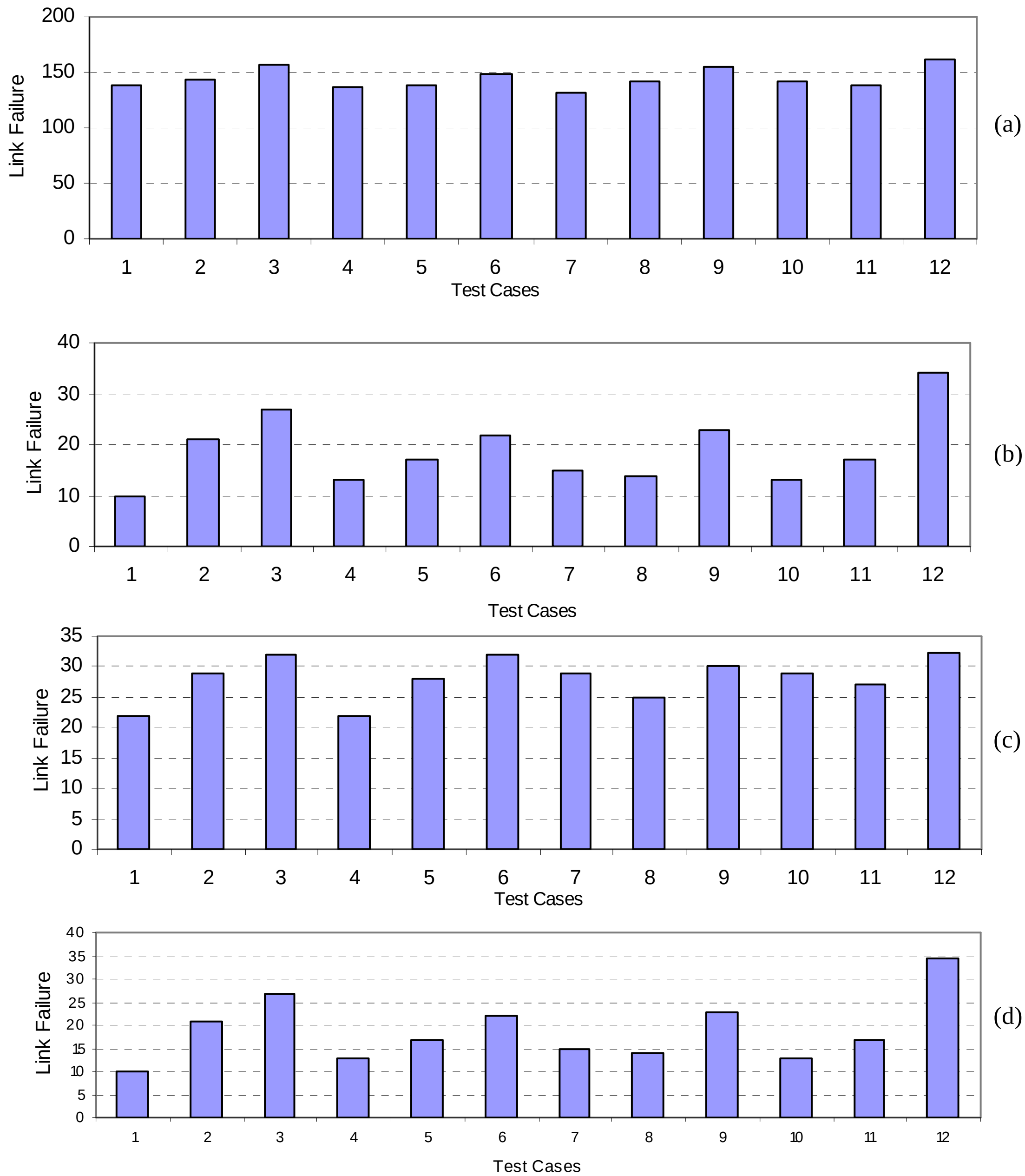


Figure 6.9 Link Failure: (a) Pause Time 0, (b) Pause Time 30, (c) Pause Time 300 and (d) Pause Time 600

Considering the mesh reliability, we observed that the *link_availability_threshold* value shows a great impact on the link failure at highly dynamic network. Both thresholds show similar impact on the link failure from intermediate to low mobility cases.

6.2.5 SRMP Robustness

In Figure 6.10, we notice that the robustness decreases with the mobility decrease. This behavior takes place in all the test cases, and is due to the construction of more recent mesh when the mobility increases (more dynamic network states). In fact, the recent mesh comprises the more recent and stable paths and thus allows more robustness.

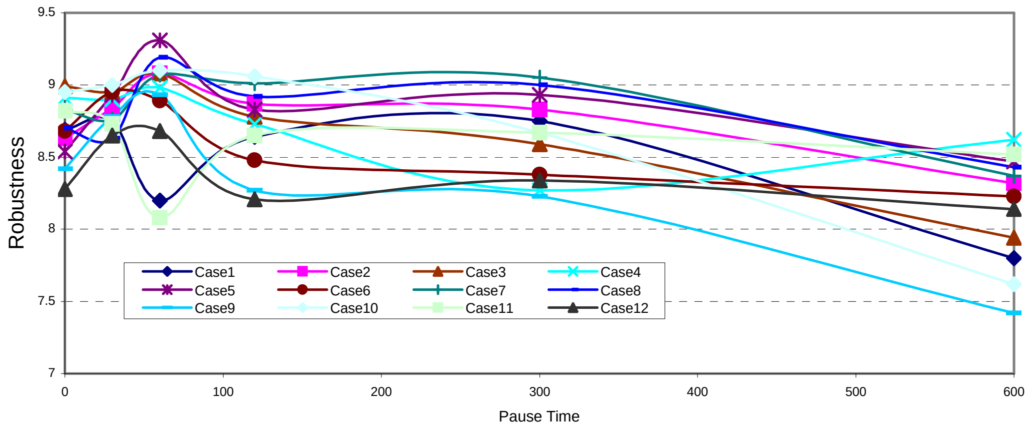


Figure 6.10 SRMP Robustness

Figure 6.11(a) and 6.11(b) show the robustness behavior with the different test cases for highly dynamic network states. An increase in robustness is noticed for higher values for the *link_availability_threshold*. Although more link failures exist in these cases (see Figure 6.9(a) and 6.9(b)), more robustness is observed due to the frequent re-construction of recent meshes. This allows the construction of more routes at each time a new mesh is established. That behavior is not shown for high *association_stability_threshold* cases, due to the low frequency of mesh re-construction at these cases. Less robustness may be caused due to link failure increase on a lower number of the constructed meshes.

For nearly static and static network cases, shown respectively in Figure 6.11(c) and 6.11(d), we notice the robustness decrease towards higher values of the *link_availability_threshold*. This comes as a result of the link failure increase at nearly the same constructed mesh or at the only constructed mesh, see Figure 6.9(c) and Figure 6.9(d). Accordingly, the number of routes connecting the multicast source to the multicast receivers is minimized. In fact, this behavior takes place for all values of the *association_stability_threshold*.

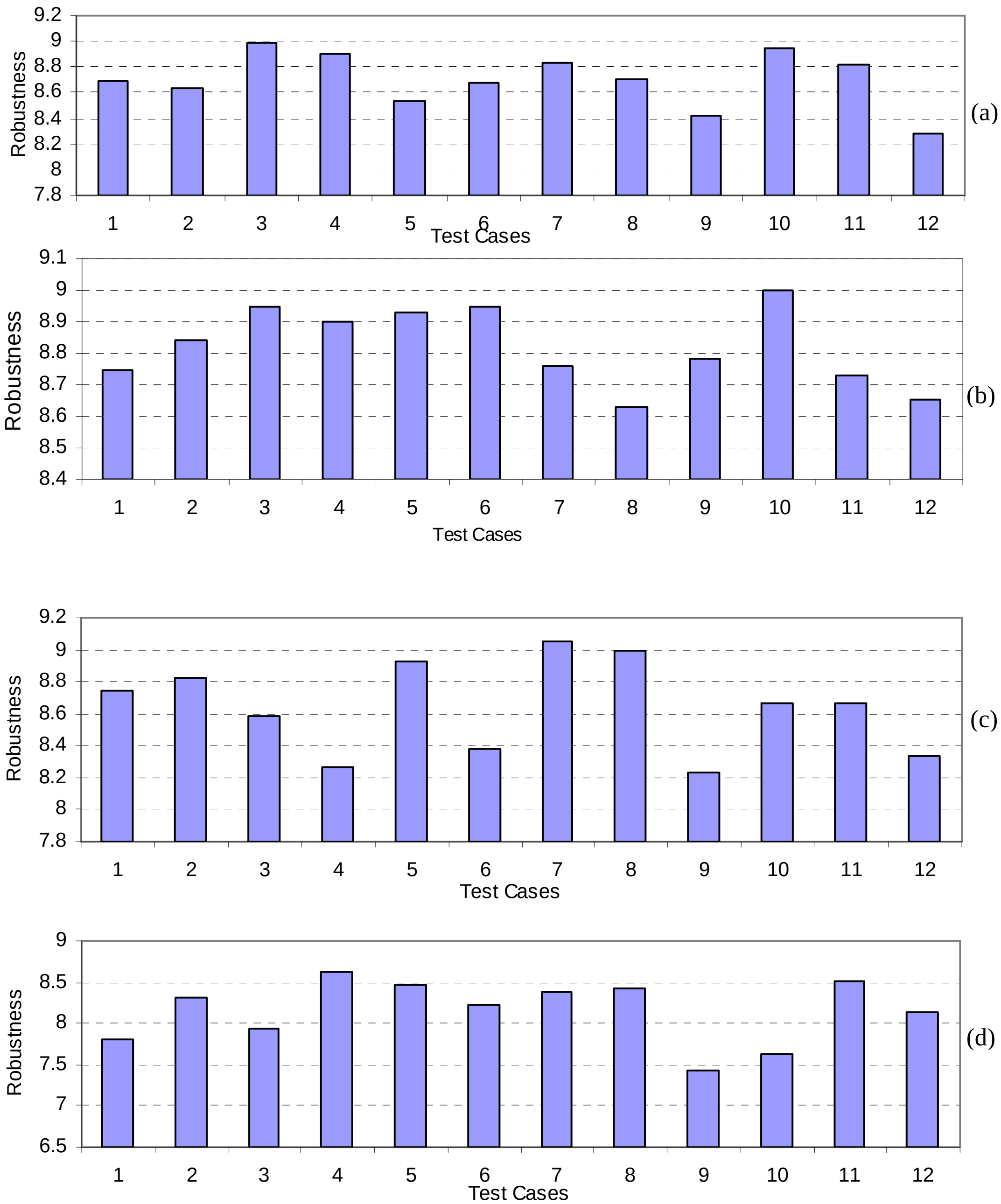


Figure 6.11 SRMP Robustness: (a) Pause Time 0, (b) Pause Time 30, (c) Pause Time 300 and (d) pause Time 600

We conclude that the *link_availability_threshold* value and the *association_stability_threshold* values show nearly the same impact on robustness at highly dynamic network. From intermediate to low mobility cases, robustness is greatly influenced by the *link_availability_threshold* value.

6.2.6 SRMP Energy Level

Figure 6.12 shows that the energy consumption decreases (energy level increases) as mobility decreases. We notice that, the minimum consumption is reached at static network (pause time 600), in all test cases except test cases 1 and 10. In fact, these two test cases show the maximum energy consumption (minimum energy level) at pause time 600. This is due to the nearly low robustness for test case 1 and the low robustness for test case 10 at this pause time (see Figure 6.10), such that the routed packets are concentrated on less number of paths, which causes relatively high delay (see Figure 6.5(d)), and also consumes more energy.

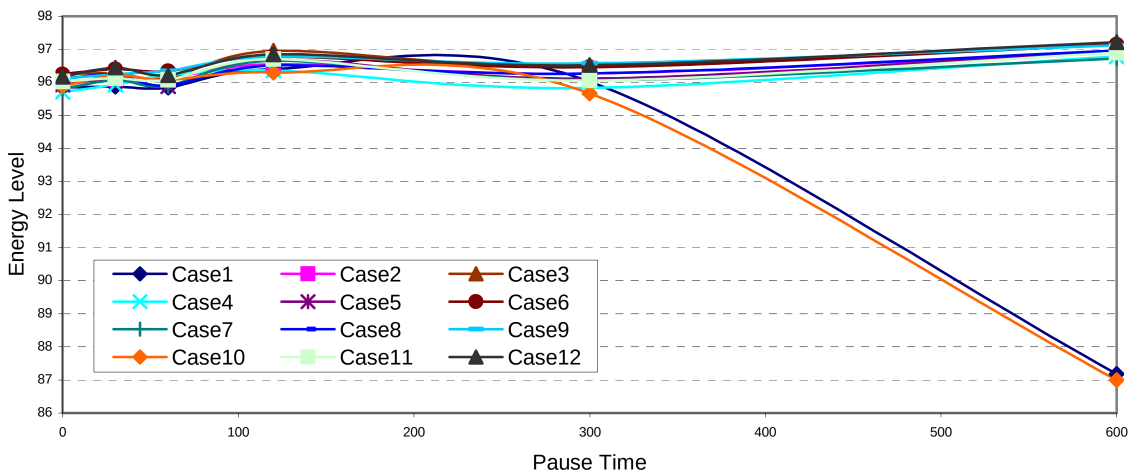


Figure 6.12 Energy Level

Figure 6.13, considers the thresholds' effect on the energy consumption, with the different test cases, for highly dynamic and static network cases. We notice that the energy consumption takes the same behavior at pause time 0 and pause time 30, see Figure 6.13(a) and 6.13(b). We observe lower energy consumption with the increase of the *link_availability_threshold* values, taking place at all values of the *association_stability_threshold*. As the *link_availability_threshold* value increases, more stable paths are constructed and the need for frequent mesh re-construction is then minimized which results in energy saving.

In Figure 6.13 (c), the same behavior takes place at this nearly static network (pause time 300). We notice a constant level of energy consumption at pause time 600, when the network reaches a steady state; see Figure 6.13 (d). This constant level is illustrated for all the test cases excluding test cases 1 and 10 where they encompass the higher energy consumption as discussed previously in Figure 6.12.

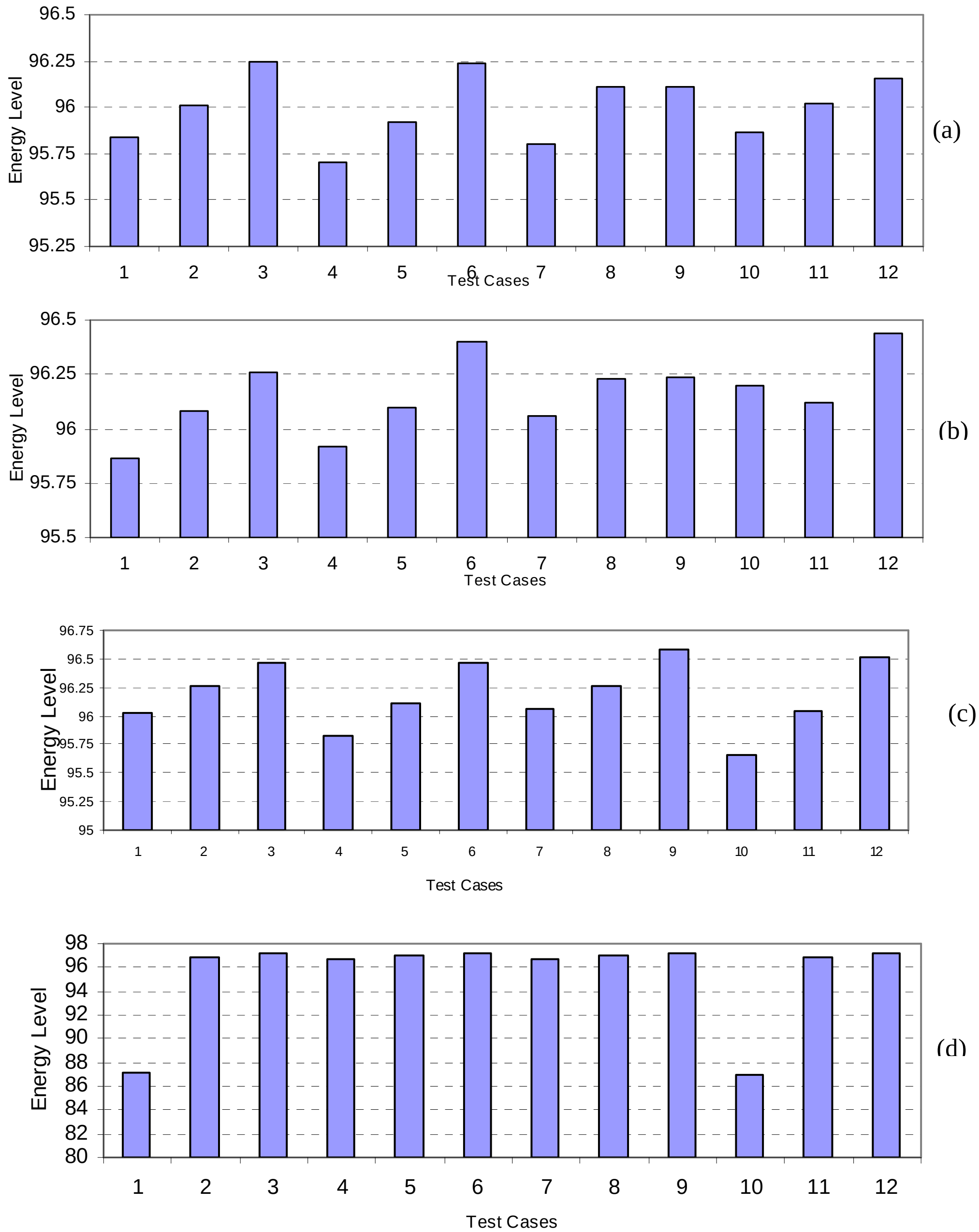


Figure 6.13 Energy Level: (a) Pause Time 0, (b) Pause Time 30, (c) Pause Time 300 and (d) Pause Time 600

We noticed that the mesh energy consumption is greatly affected by the *link_availability_threshold* value for nearly all types of mobility. However, the *association_stability_threshold* value starts to have more impact on the energy consumption when the network tends to be stationary.

6.3 Summary and Conclusion

In this chapter we presented an adaptive study on the choice of thresholds' values for our selection metrics, reflecting the connectivity quality. Based on the ensemble of thresholds the characteristics of the constructed mesh (robustness, reliable transmission, and less energy consumption) may vary substantially, and hence affect the performance.

A key goal is to determine a successful set of thresholds that allows the construction of a suitable and a reliable mesh, and hence provides an improved performance for our protocol. We investigated 12 combinations of different values for the *association_stability_threshold* and the *link_availability_threshold*, while we fixed the *signal_strength_threshold* together with the *energy_level_threshold*. We have chosen the *signal_strength_threshold* value so as to guarantee an acceptable received signal power and to assure correct reception, while the *energy_level_threshold* was calculated as a function of time.

A brief summary for our analysis results is presented in Table 6.2, showing the thresholds' impact on our protocol performance and the mesh efficiency. Where the term *Linav* signifies the impact of the *link_availability_threshold*, and the term *Ass_stat* signifies the impact of the *association_stability_threshold*. The number of (+) signs increase signifies a more impact. While the number of (-) signs increase signifies lower impact.

Table 6.2 SRMP Thresholds' Impact: Results Summary

Network State	Performance Metrics						Mesh State
	Delivery Ratio	Delay	Overhead	Link Failure	Robustness	Energy Level	
Hyper Mobility	Linav +++ Ass_stat ++	Linav ++ Ass_stat +++	Linav +++ Ass_stat ++	Linav +++ Ass_stat +	Linav +++ Ass_stat ++	Linav +++ Ass_stat +	Quite sparse-very short lifetime
High Mobility	Linav +++ Ass_stat +	Linav +++ Ass_stat +	Linav +++ Ass_stat ++	Linav +++ Ass_stat ++	Linav +++ Ass_stat ++	Linav +++ Ass_stat +	Sparse –lack paths' availability
Nearly Static	Linav +++ Ass_stat ++	Linav +++ Ass_stat +++	Linav +++ Ass_stat +++	Linav +++ Ass_stat +++	Linav +++ Ass_stat +	Linav +++ Ass_stat +	Denser – more lifetime
Static	Linav +++ Ass_stat +++	Linav +++ Ass_stat ++	Linav +++ Ass_stat +++	Linav +++ Ass_stat +++	Linav +++ Ass_stat +	Linav +++ Ass_stat ++	Densest – nearly stable-maximum liftime

In general, the choice of thresholds' values should differ according to the type of mobility. Accordingly, we highlighted the impact of thresholds variations, which influence the connectivity quality estimate, on the performance of SRMP. Also, we strongly conclude the necessity of developing an adaptive mechanism that allows the thresholds' adjustment as a function of the mobility type.

In the next chapter, we model the mesh construction process in SRMP using random graph modeling. We propose a Reactive Random Graph (RRG), to study the behavior of some important mesh properties that provide reliable connectivity.

CHAPTER 7 REACTIVE RANDOM GRAPH (RRG)

A network can be represented mathematically by a graph $\boldsymbol{G} = \{\boldsymbol{V}, \boldsymbol{E}\}$, where $\boldsymbol{V}$ is a set of N nodes or vertices and $\boldsymbol{E}$ is a set of edges or links that connects two elements of the set $\boldsymbol{V}$. Two vertices are being joined by an edge if the corresponding nodes in the network are connected.

In this chapter, we study the random graph as a model of complex networks, and we investigate the phase transition behavior that emerges for some random graph properties. The objective of our study was to exploit the random graph in modeling an ad hoc network environment. More precisely, our target was to analyze the performance of our proposed multicast protocol SRMP, using the random graph theory.

A random graph is a graph in which properties such as the number of graph vertices, graph edges, and connections between nodes follows a random mean. Random graph theory is regularly used in the study of complex networks, such networks comprise a complex topology and unknown organizing principles, which often appear randomly.

7.1 Introduction

The theory of random graphs was initiated by the Hungarian mathematicians *P. Erdös* and *A. Rényi* in the 1950's [Erd59], after *Erdös* had discovered that probabilistic methods are often useful in tackling extremal problems in graph theory. Since then, a large number of results had been achieved [Bol01].

Erdös and *Rényi* gave a number of versions of their model. In their classical model which is known as the $G_{N,M}$ model [Alb02], they define a random graph as N labeled nodes connected by M edges, which are chosen randomly from $N(N-1)/2$ possible edges. The most commonly studied model is the one denoted by $G_{N,P}$ [New02], in which each possible edge between two vertices is present with independent probability P, and absent with probability $1- P$.

The main goal of random graph theory is to determine at what connection probability *P* a particular property of a graph will most likely arise. Some properties of random graphs show interesting behavior around a transition point, which is the characteristic of phase transition explored from the percolation theory [Alb02].

Random graphs are highly attractive in modeling and analyzing the ad hoc routing protocols. Before our orientation towards random graph modeling, we tackled two other approaches. Firstly, we considered Markovian chain to analyze the performance of SRMP in terms of the call blocking probability [Ros95]. We noticed that this solution is not scalable, as the traditional Markov models lead to an exponential explosion of state space very quickly. Accordingly, we studied the use of approximation algorithms like the Fixed Point Approximation (*FPA*) [Liu04], but we discovered that this approach is most suitable in modeling problems of queuing systems. Furthermore, these modeling approaches tackle the problem of channel access rather than the routing efficiency. On the contrary, the random graphs are more suitable in modeling communication networks: many difficult algorithmic problems that defy scalability become much easier for random graphs. Furthermore, some critical properties in random graphs start to appear around a transition point. This is the characteristics of phase transition [Alb02] explored from percolation theory [Stu92]. It was discovered that hard to solve problems occur at such boundaries for many types of problems [Che91].

In the next section, we give a brief review on random graph models for MANETs. In Section 7.3, we propose a reactive random graph for modeling the SRMP protocol. Our analysis and results are respectively presented in Section 7.4 and Section 7.5. Random graphs are further explored in Appendix B.

7.2 Random Graphs as Models of MANETs: Related Work

Ad hoc networks are described as networks with complex topology, which is difficult to analyze. Mathematical models of random graphs and percolation theory have been recently explored for providing useful solutions in MANETs. Percolation theory [Stu92] mainly studies the formation and structure of clusters (connected area) in a large lattice. The long-term goal is to develop reliability specifications and ensure network connectivity in spite of link failures.

A random graph model is explored in [Dow01] to evaluate connectivity in distributed sensor networks (*DSNs*). The connectivity property is also studied for both purely ad hoc networks and hybrid networks in [Dou02, Kri01] to evaluate the probability that two random nodes are connected. Their results show a phase transition at a critical node density, otherwise network division takes place.

A gossiping-based approach is proposed in [Haa02] allowing probabilistic flooding, reducing the routing overhead while ensuring the required message dissemination. It was proved in this work that adding gossiping to AODV improves the number of messages sent as well as network performance in terms of end-to-end latency and throughput. Probabilistic flooding is also defined in [Sas02], where the rate of successful packet delivery demonstrates a phase transition affected by the network size and the average node degree.

Using the random graph properties, an analysis of ad hoc networks is studied in [Far02], proposing a solution for designing an appropriate transmission radius in ad hoc networks. An admission control and power control schemes are proposed in [Chia01], where links are chosen to guarantee stability of the connection.

An analysis of ad hoc routing performance is proposed in [Jac99] using random graph models. The goal is to compare reactive and proactive unicast protocols, via comparing the route non-optimality in the former with respect to the periodic control traffic overhead in the latter.

Ad hoc networks have a complex topology, constrained with limited resources and facing many routing challenges. Accordingly, it is difficult to model and analyze such networks and it is hard to analyze their routing problems. An important objective is to provide scalable modeling approaches, which do not involve exponentially growing computation and can support the dynamic and unpredicted topology.

Due to problem complexity, small contributions only exist. Most of the existing models work under the assumption of no mobility and depend on many expected values. Concerning the routing problem, we noticed only few propositions for unicast routing analysis. To our knowledge, no analytical model has been proposed until now for analyzing a multicast routing protocol.

7.3 SRMP Modeling

In this section, we derive an analytical model for our SRMP protocol. Our model is investigated from the random graph theory, exploiting phase transition behavior from the percolation theory. To our knowledge, so far no analytical model has been proposed to analyze a multicast routing protocol in ad hoc networks.

7.3.1 Problem Definition

An important goal to achieve in ad hoc multicast routing is making efficient use of the network resources and providing reliable communication to assure connectivity of all multicast group members. Our proposed routing protocol, *SRMP*, succeeds in providing reliable communication between multicast group members while economizing the network resources use. This is achieved via constructing a robust mesh topology for each multicast group.

Our purpose is to model the mesh as a communication graph via exploring the theory of random graphs, and to make use of this model in validating key features of *SRMP*. We aim to develop a reliable communication graph via selecting a set of links, as a function of their communication capabilities.

If the network is modeled as a graph $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$ where $\boldsymbol{V}$ is the set of vertices representing the nodes and $\boldsymbol{E}$ is the set of edges representing the links between nodes, then we wish to connect a set $\boldsymbol{D} \subseteq \boldsymbol{V}$ that represents the communication graph vertices. Assuming that we have one multicast group with only 1 source, then $\boldsymbol{D} = \{\{\boldsymbol{R}\}, \boldsymbol{S}, \{\boldsymbol{F}\}\}$. Given that, $\boldsymbol{R} \subseteq \boldsymbol{V}$ represents the multicast receivers, $\boldsymbol{S} \in \boldsymbol{V}$ represents the multicast source, and $\boldsymbol{F} \subseteq \boldsymbol{V}$ represents the network nodes or graph vertices that grants the connection between $\boldsymbol{S}$ and $\boldsymbol{R}$.

SRMP works in a reactive mean: at the time the connection is requested, the communication graph (mesh) is constructed on the set $\boldsymbol{D}$ such that it assures connectivity within $\boldsymbol{S}$ and the set $\boldsymbol{R}$, while including the set $\boldsymbol{F}$. This is achieved via selecting minimum cost paths. Our design problem is finding the optimum communication graph (mesh), comprising the minimum possible number of links, while assuring connectivity between $\boldsymbol{S}$ and the set $\boldsymbol{R}$.

7.3.2 The Communication Graph Definition

Let us consider a definition for the communication graph problem. Firstly, we start by a simple definition considering the case of a wireless static network where every node is only reachable from its neighbor(s). We denote $\boldsymbol{G_c} = (\boldsymbol{D}, \boldsymbol{L})$ our communication graph, such that $\boldsymbol{D} \subseteq \boldsymbol{V}$ is the set of vertices of the graph and is equal to $\{\{\boldsymbol{R}\}, \boldsymbol{S}, \{\boldsymbol{F}\}\}$ and $\boldsymbol{L}$ is the set of all possible edges over $\boldsymbol{D}$. The function, ***Edges***: $\boldsymbol{L} \rightarrow \boldsymbol{Z}^+$ gives us an estimate of connectivity among the vertices and the size of $\boldsymbol{G_c}$. We define a connection request $\boldsymbol{C} = (\boldsymbol{M}, \boldsymbol{r})$ such that $\boldsymbol{M} \subseteq \boldsymbol{D}$ is the set of vertices required to be interconnected and is equal to $\{\boldsymbol{S}, \{\boldsymbol{R}\}\}$ and $\boldsymbol{r}$ is the required communication capability. The function, ***Metric***: $\boldsymbol{r} \rightarrow \boldsymbol{R}^+$ gives us the requirement for setting up the connection including battery consumption as well as availability of nodes constituting the links and the nature of the radio propagation. Finally, we define the paths (routes) for the connection request $\boldsymbol{C} = (\boldsymbol{M}, \boldsymbol{r})$ to be the connected subgraphs of $\boldsymbol{G_c}$, where each path in $\boldsymbol{G_c}$ is defined as $\boldsymbol{P_c}(\boldsymbol{d}, \boldsymbol{l})$ such that $\boldsymbol{d} \subseteq \boldsymbol{D}$ and $\boldsymbol{l} \subseteq \boldsymbol{L}$. All the paths should satisfy the request $\boldsymbol{C} = (\boldsymbol{M}, \boldsymbol{r})$ and are defined as **Sum** $\{\boldsymbol{P_{ci}}(\boldsymbol{d_i}, \boldsymbol{l_i}),\ i=1 \rightarrow n,\ n$: total number of paths$\}$. In other words, they can be defined as all the possible paths constituting the communication graph. Note that the set of links $\boldsymbol{l}$ on each path $\boldsymbol{P_c}(\boldsymbol{d}, \boldsymbol{l})$ is set up according to the ***Metric*** function.

7.3.3 The Reactive Random Graph (RRG) Model

In *SRMP*, the communication graph $\boldsymbol{G_c} = (\boldsymbol{D}, \boldsymbol{L})$ is constructed as a random graph, where the set of vertices $\boldsymbol{D}$ are distributed randomly in the two-dimensional plane (our network topography) such that an edge $\boldsymbol{e} \in \boldsymbol{L}$ connecting two vertices exists if the constraints in Section 7.3.2 are satisfied. The set of edges and the resultant graph connectivity are emergent properties of the random graph, they depend on locations of the vertices and their communication capabilities.

In the sequel, we use the words nodes/vertices, network/graph, and links/edges interchangeably, and N denotes the number of nodes constituting the *RRG*, while i and j denote any pair of nodes among N.

Actually, our communication graph setup takes place in a reactive mean: when a source has a certain request to transmit its data, and edges existence depends on the communication capability (satisfaction of certain criteria) between each node's pair. Based on these facts, the name Reactive Random Graph (***RRG***) model is inspired.

Given a communication network of size N vertices, a graph G is constructed in a reactive mean among the N vertices such that there is an edge between each pair of vertices i, j with probability $p_{i,j}$, reflecting the links' selection criteria in *SRMP*. In fact, the presence or absence of a direct link (edge) between each pair of nodes (vertices) occurs with probability $p_{i,j}$. When $p_{i,j} = 0$, the resulting random graph has no edges and each node is isolated, while when $p_{i,j} = 1$, we obtain a qualitative communication among the communication graph vertices. Typically, different connectivity quality levels take place within the interval [0, 1] of $p_{i,j}$.

The probability $p_{i,j}$ encounters several design criteria for each link setup, such that:

(i) neighborhood between nodes should respect the nodes' radio range.

(ii) availability of each pair of nodes constituting each link.

(iii) minimum possible cost link in terms of its both nodes battery consumption.

(iv) quality limit for each link in terms of signal strength.

As ad hoc multicast routing problem is complicated by the fact that the set $\boldsymbol{D}$ may move and/or change during the lifetime of the connection, we evaluate graphs of fixed vertices as a model of static ad hoc network exhibiting no mobility (this is an ideal case within some applications), or as a discrete time "snapshot" of a realistic ad hoc network. Therefore, our probability $\boldsymbol{p_{i,j}}$ is a discrete time probability that is invoked instantaneously, thus we denote it by $\boldsymbol{p_{i,j}}$ $(\boldsymbol{t})$ and consequently we denote the *RRG* model by $\boldsymbol{G_{N,p}(t)}$. In our analysis, we assume that $\boldsymbol{t}$ is constant, applying only one value of $\boldsymbol{t}$, and that the locations of the N nodes are uniformly distributed within the two-dimensional geographical area.

Note that any other distribution may be also used. Furthermore, we assumed that this graph is undirected.

7.3.3.1 The Link Probability Features

We consider several factors that affect the probability of a link existence, $\boldsymbol{p_{i,j}(t)}$, between any nodes' pair i and j. We aim to model the ad hoc network environment together with our routing protocol characteristics, including the distance between the nodes, the presence of obstacles, the reception quality and the energy consumption. The main factors affecting $\boldsymbol{p_{i,j}(t)}$ are:

a) *Radio Transmission Range*: we consider a mesh of N nodes. Given i and j as any two nodes pair, L_i and L_j are two random variables indicating respectively their locations, then $d = | L_i - L_j |$ denotes the Euclidean distance (separation distance) between them. The existence of a direct radio link between i and j depends on the value of d.

b) *Obstacles Consideration and Link's Quality*: we take into account the nature of the radio environment through considering some features that influence any nodes pair communication, as the presence of obstacles. In a continuous highly dynamic scenario each node encompasses frequent appearance/disappearance that is translated as availability/unavailability. Furthermore, we assume that certain link's quality limits should be satisfied between any nodes pair wanting to communicate. Our motivation to this assumption is due to the fact that bad quality links are most probably susceptible to vanishing, affecting the reliability of our communication network, and they do not provide trustworthy transfer.

c) *Battery Level*: since SRMP seeks at economizing the battery resource in order to assure reliable data transfer, we assume that the presence of a link between each nodes pair i, j requires an adequate battery level for both nodes. The presence of a link thus depends on its cost in terms of battery consumption.

7.3.3.2 The Key Components of RRG

Mainly, there are three key components constituting the *RRG* model:

- A set of random variables $\{L_i, B_i, A_{shi,j}\}$ associated with each node i;

  $\boldsymbol{L_i}$: a random variable indicating the random location of node i, it is uniformly distributed within the geographical area of the network.

  $\boldsymbol{B_i}$: a random variable indicating node's i current battery level as a function of the consumed energy until instant t, assuming that all nodes have the same initial battery level. Its value is taken from the interval [0,1]

$\boldsymbol{A}_{shi,j}$: a random variable concerning the radio propagation model signal quality, taking its value from R and indicates the shadowing effect on the reception at node j due to a transmission at node i. It depends on the radio environment and the distance between the two nodes.

- A probability $p_a(i, j)$ associated with each link between any pair of nodes i and j indicating the probability of the link's existence between this pair of nodes;

  $\boldsymbol{P_a}(i, j)$: reflects the probability of the link's availability between each nodes' pair i and j in terms of the distance between the two nodes, the shadowing effect of the radio channel, and the level of the received signal. It maps the location random variables (L_i, L_j), and the signal quality random variable ($\boldsymbol{A}_{shi,j}$) into a real number in the interval [0, 1].

- A cost function $f_c(i, j)$ associated with each link between any pair of nodes i and j indicating the cost of this link in terms of battery power consumption;

  $\boldsymbol{f_c}(i, j)$: is a cost function that reflects the link energy level between any nodes' pair i and j. It gives an estimate of the minimum link cost through mapping the battery random variables (B_i, B_j) into a real number in the interval [0, 1].

Considering the previous criteria and the above definitions, the probability $\boldsymbol{p}_{i,j}(\boldsymbol{t})$ for a link existence between each nodes' pair i and j is given by Equation 7.1.

$$\boldsymbol{p}_{i,j}(\boldsymbol{t}) = \boldsymbol{p_a}(i, j) . \boldsymbol{f_c}(i, j) \tag{7.1}$$

$\boldsymbol{p_a}(i, j)$ and $\boldsymbol{f_c}(i, j)$ are derived in the next two sections.

7.3.3.3 Radio Propagation Model and Links' Availability ($\boldsymbol{p_a}(i, j)$)

The used radio propagation model takes into account the surrounding environment and describes the shadowing effects, which occur over a large number of locations having the same separation distance. This propagation model extends the ideal circle model [Rap96], which predicts the received power as a deterministic function of distance, to a richer model where nodes can only probabilistically communicate when they are near the edge of the communication range.

Consequently, we predict the received power at node j corresponding to a transmission from node i to be as follows:

$$\boldsymbol{P}_r = \boldsymbol{K} . \boldsymbol{P}_t . \frac{1}{d^{\alpha}} . \boldsymbol{A}_{sh\,i,j} \tag{7.2}$$

$\boldsymbol{P}_r$: Predicted received power in dB
$\boldsymbol{K}$: A constant, its value depends on the radio environment
$\boldsymbol{P}_t$: Transmitted power in dB
$\boldsymbol{d}$: Separation distance between i and j and equal to $| \boldsymbol{L_i} - \boldsymbol{L_j} |$

> α: Path loss exponent, its value depends on the environment ($2 \leq \alpha \leq 4$)
> $A_{sh\ i,j}$: log-normal random variable reflecting the variation of the received power according to the surrounding radio environment, it is of Gaussian distribution as it is measured in dB, with zero mean and standard deviation (shadowing deviation) σ_{dB}

As a quality constraint, we consider the sensitivity of reception assuming shadowing deviation to be zero and the separation distance between the nodes pair to be the maximum possible $\mathbf{d}_{max}$ (equal to the radio range *rr*). Thus, we calculate the power reception sensitivity P_{sens} as follows,

$$P_{sens} = P_r(d\max, \sigma_{dB} = 0) = K.\, P_t.\, \frac{1}{d\max^{\alpha}}.\, \mathbf{1} \qquad (7.3)$$

From the above formulation, the existence of a direct radio link between *i* and *j* requires a good reception quality between the two nodes. To provide link availability, the reception quality considers the shadowing effect and the separation distance between the two nodes. We denote the probability of having a good quality link between *i* and *j* by $p_a(i, j)$;

$$p_a(i, j) = 1 - \text{Packet Error Rate (PER)} = 1 - \mathbf{P}(\text{reception failure}) \qquad (7.4)$$

$$\mathbf{P}(\text{reception failure}) = \mathbf{F}(P_r - P_{sens}) \qquad (7.5)$$

$$\mathbf{F}(P_r - P_{sens}) = \begin{cases} 1 & if\ P_r < P_{sens} \\ x \in [0,1] & if\ P_r \geq P_{sens} \end{cases} \qquad (7.6)$$

7.3.3.4 Minimum Cost Links ($f_c(i, j)$)

B_i and B_j denote two random variables representing respectively nodes *i* and *j* current battery levels. To assure reliable communication, τ denotes a threshold for the adequate current battery level, its value is chosen from the interval [0,1] and it depends on the initial battery power, time instant *t*, and the number of nodes *N*. Then $D(B_i, B_j)$ denote a decision function reflecting the adequacy of the link between *i*, *j* nodes pair.

$$D(B_i, B_j) = \begin{cases} 1 & if \quad Bi \geq \tau \quad and \quad Bj \geq \tau \\ 0 & if \quad Bi < \tau \quad or \quad Bj < \tau \end{cases} \qquad (7.7)$$

Accordingly, we assume that the existence of a minimum cost link between *i* and *j* depends on an energy resource constraint, where the probability of having a minimum cost link between them is indicated by the function $f_c(i,j)$ given by Equation 7.8:

$$f_c(i, j) = D(B_i, B_j).\min\lfloor B_i, B_j \rfloor \qquad (7.8)$$

f_c is the minimum cost fucntion. As mentioned in Section 7.3.3.2, f_c takes its value from the interval [0, 1], such that when its value tends to 1 it indicates minimum link cost.

It follows from Equation 7.4 to 7.8 that the nodes' locations in the RRG are not the only factor that affect the probability of links' existence. The link (edge) probability in *RRG* is not constant; rather it varies for different nodes' pair. Thus the name *RRG* is inspired.

7.4 Analysis

The main goal of our modeling approach is to determine when certain graph properties are likely to appear in our communication graph (mesh). The fulfillment of some properties helps to find the optimum communication graph in terms of the minimum possible number of edges while assuring the connectivity between {*R*} and *S*. Consequently, we study the conditional probabilities for the fulfillment of certain properties in the communication graph.

In our analysis, we aim to answer the following questions: what is the probability for a vertex within {{***R***}, ***S***} to be isolated (degree = 0)? What is the probability of having a link between any nodes pair (i.e. link connectivity)? What is the probability of graph connectivity (i.e. each vertex of {***R***} is connected to ***S***)? What is the edge probability after which the communication graph has nearly the same size (in terms of the number of edges)?

Most of the above properties are first order properties [Bol01]. The following definitions illustrate three first order graph properties that influence our communication graph connectivity,

Definition 1: Property 1 = *"No vertex* **r** *from the set {**R**} is isolated and no vertex* **s** = **S** *is isolated"*

$$\{\forall r, \exists x \text{ s.t.}\{ E(r, x) \wedge \{(x = s) \vee \neg(x = s)\}\}\} \wedge$$
$$\{\forall s, \exists x \text{ s.t.}\{ E(s, x) \wedge \{(x = r) \vee \neg(x = r)\}\}\}$$

Where $E(vertix_1, vertix_2)$ indicates that there is an edge between $vertix_1$and $vertix_2$.

Definition 2: Property 2 = *"There exists an edge between any pair of vertices x, y"*

$$\forall x, \exists y \text{ s.t. } E(x, y)$$

Definition 3: Property 3 = *"There exists at least one path p between the vertex s =* **S** *and each vertex r from the set {**R**}, given that k is path length such that k ≥ 1"*

$$\forall s, \forall r \, \exists p(s, r) \text{ s.t. } \{ \{\exists x_1 \text{ s.t.}\{E(s, x_1) \wedge (x_1 = r)\}\} \vee$$
$$\{ \{\exists x_1 \text{ s.t.}\{ E(s, x_1) \wedge \neg(x_1 = r) \}\} \wedge$$
$$\{\exists x_2 \text{ s.t.}\{ E(x_1, x_2) \wedge \neg(x_2 = r, s) \}\} \wedge$$
$$\{\exists x_3 \text{ s.t.}\{ E(x_2, x_3) \wedge \neg(x_3 = r, s, x_1) \}\} \wedge$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\{\exists x_k \text{ s.t.}\{ E(x_{k-1}, x_k) \wedge \neg(x_k = r, s, x_{k-2,\ldots\ldots\ldots,} x_1) \}\}$$
$$\}$$
$$\}$$

Since first order properties proved to show a phase transition [Bol01], then we conclude that *property 1*, *property 2*, and *property 3* undergo a zero-one transition or more precisely a property transition in our *RRG*. In the following section, we numerically investigate our formal modeling for *SRMP*, and study the behavior of these properties in the context of phase transition. We also analyze other critical features that grant optimum mesh size versus robustness.

7.5 Results and Discussion

From our previous analysis, we investigate some properties reflecting the *RRG* connectivity, or in other words our communication graph (mesh) robustness and optimum size in terms of the number of edges. We precisely deal with the following characteristics and properties:

- *Mesh density*: The total numbers of edges constituting the communication graph (mesh), more precisely the connex part involving the source node.
- *Multicast receivers connectivity*: The ratio of the connected multicast receivers to the total number of receivers.
- *Multicast Group connectedness*: The total number of paths constructed for the multicast group.
- *Receiver connectedness*: The total number of the constructed paths, connecting each receiver with the source.

We denote $\boldsymbol{N}$ as the total number of nodes constituting the mesh, and we deal with the *Average edge probability* which is defined as the average of $\boldsymbol{p_{i,j}}$ (t), defined in Equation 7.1, calculated $\forall$ pair of nodes *i*, *j*.

We assume the following hypothesis during our analysis: -

Hypothesis 1: *The radio transmission range (rr) is constant for all nodes, such that* $\forall i \in N$, *rr = constant = 1.*

Hypothesis 2: *The two dimensional geographical space is a square of side D with variable surface area and constant density, such that the nodes number is proportional to the surface area;*

$$\mathrm{N} \propto D^2 \quad \Rightarrow \quad D = \text{const.} \sqrt{N} \quad \Rightarrow D = \lceil 2 * \sqrt{N} \rceil$$

Hypothesis 3: The multicast group size *G* (source + receiver(s)) is multiple of 2, such that $G = 2^n$ where *n* is an increasing function of *N*.

In this section, we analyze our results for two communication graph (mesh) types, small graphs in which $\boldsymbol{N}$ = 10, 15, 20, and large scale graphs in which $\boldsymbol{N}$ = 100, 200, 300, 400, 500. We show the average results for 1000 differently generated *RRG*. As mentioned previously, we define our geographical area as an *m* x *m* square, such that *m* = *D*. Nodes are placed randomly with uniform distribution in this area, and each node can directly communicate with any other node in its surrounding if there is an edge between them.

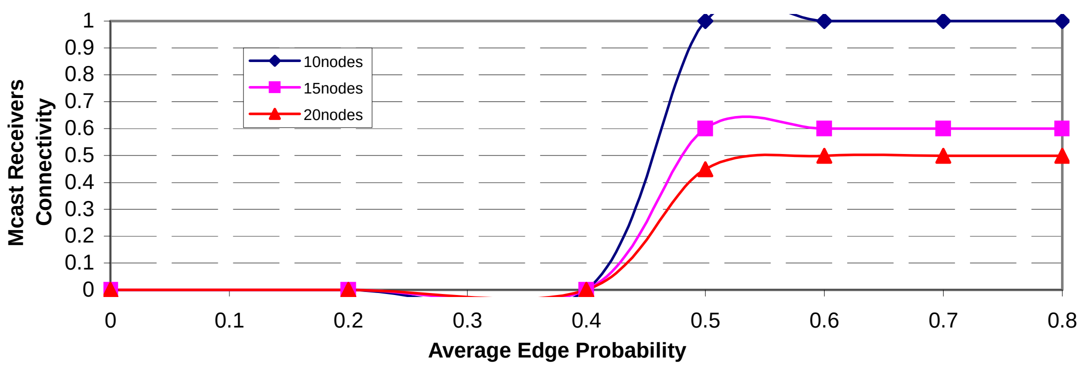


Figure 7.1 Small Size Graph: Average Edge Probability versus Multicast Receivers Connectivity

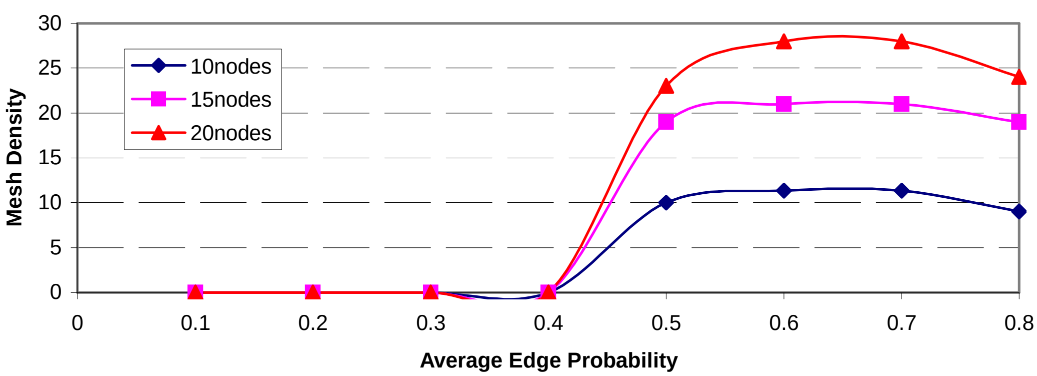


Figure 7.2 Small Size Graph: Average Edge Probability versus Mesh Density

Concerning the multicast group size, for small graph's size we chose the values of *n* to be equal 1, 2 , 3 for *N* = 10, 15, 20 respectively. While for large graph's size we chose the values of *n* to be equal 4, 5, 6, 7, 8 for *N* = 100, 200, 300, 400, 500 respectively. Through our analysis, we consider that $p_{i,j}$ (t) is the edge probability (the probability of having an edge between each pair of nodes at an instant (t)).

The edge probability in *RRG* takes a reactive mean, i.e., its value is not constant for each pair of nodes but rather depends on the satisfaction of certain criteria for each node's pair in the communication graph, as mentioned in Section 7.3.3. Actually, the value of $p_{i,j}$ (t) does not reflect a quantitative meaning for an edge existence but rather a qualitative meaning. In other words, the main concept or idea that differentiates our *RRG* model from other random graph models is that the higher the value of the edge probability $p_{i,j}$ (t), the higher the expected quality of the link which exists between the node pair *i*, *j*.

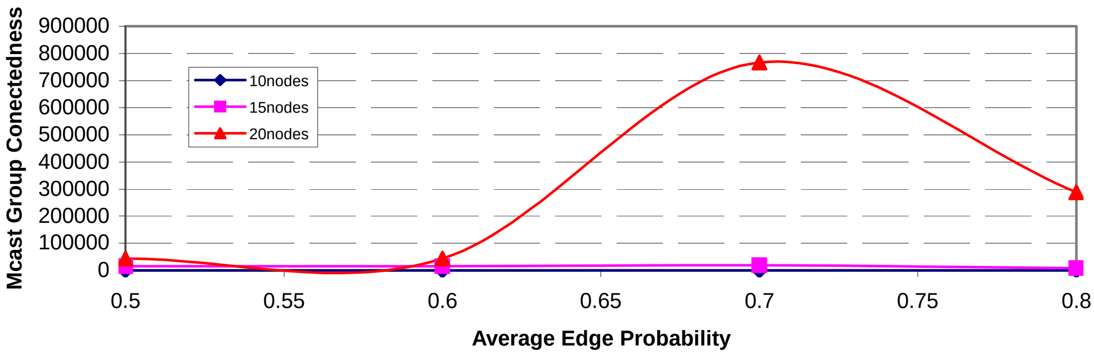


Figure 7.3 Small Size Graph: Average Edge Probability versus Multicast Group Connectedness

We illustrate our analysis results for small size communication graph through Figure 7.1 up to Figure 7.7, while large-scale communication graph results are illustrated through Figure 7.8 up to Figure 7.11.

In Figure 7.1, we analyze the efficiency of the communication graph in terms of covering all the receivers' nodes. More precisely, we study the evolution of the multicast receivers connectivity with different average edge probability. We notice the sharp behavior common to many phase transition results. The critical probability or the crossover point is found to be at about 0.4. Thus, if the average edge probability is below 0.4, the receivers are totally disconnected. At average edge probability equal 0.4, a phase transition takes place from zero receivers connectivity to full receivers connectivity at N = 10, 60% receivers connectivity at N = 15, and 50% receivers connectivity at N = 20. Furthermore, this sharp behavior provides stable connectivity for average edge probability > 0.4.

In mapping this behavior with the criteria influencing $\boldsymbol{p}_{i,j}$ (t) value, we can say that below the crossover point either no edges exist or the edges that exist are not sufficient to cover any of the receivers. A third but very important reasoning, which is the core of the *RRG* model, is that the qualitative edges start to exist after the crossover point and thus promoting connectivity to appear causing this sharp transition. The stable behavior following the sudden transition is due to the satisfaction of the required criteria when the average edge probability ≥ 0.4 and thus allowing a steady receivers connectivity with different levels for different values of N (communication graph size).

Figure 7.2, demonstrates the mesh density versus the edge existence between any pair of vertices in the communication graph. A phase transition also arises at the same crossover point (0.4). When the average edge probability is below 0.4, a zero edge existence property takes place, translating the no-connectivity behavior below this crossover point in Figure 7.1. On the other hand, edges existence appears between nodes' pairs when the average edge probability > 0.4 and thus resulting in the receivers connectivity starting from this crossover point as shown in Figure 7.1. The different levels for the three curves after the crossover point is due to the different values of *N* (communication graph size), where the mesh density is directly proportional to *N*.

We notice here that the phase transition does not take a stable form after the crossover point, however it takes the behavior of a nearly bell curve. As mentioned before, the edge probability in the *RRG* model gives an indication of the validity (quality level) of the edges, and does not reflect a quantitative meaning but rather a qualitative meaning. In other words, the highest probability value does not mean more chance to have edges as in traditional modeling of the random graph where the edges existence is a function of the edge probability value. It is noticed in Figure 7.2 that as the average edge probability tends to its maximum possible value, the density in terms of the number of edges decreases tending to optimize communication graph size, while the connectivity is not affected as shown in Figure 7.1. Accordingly the communication graph provides the suitable connectivity, reflecting the robustness, with less density or more optimum size.

Figure 7.3 shows the evolution of the constructed paths for the multicast group with the average edge probability. The obtained results come as a consequent for our analysis in Figure 7.1 and Figure 7.2, where the multicast group connectedness takes a clear bell curve form. This is obvious at $N = 20$, while it is not so clear at $N = 10, 15$ due to the large difference in scale but they are also bell curves like. Actually, the bell curve tends to reach its maxima at average edge probability interval [0.6, 0.7] where the communication graph becomes denser at this interval, see Figure 7.2. At higher values of the average edge probability the bell curve starts to degrade due to the optimization of the graph density in terms of the number of edges, as noticed in Figure 7.2. Accordingly, less number of routes covers the multicast group; meanwhile the connectivity is not influenced as noticed in Figure 7.1.

An interesting behavior for the receivers' connectivity is illustrated in Figure 7.4. We notice that for all values of *N* when the mesh density < $N\log N/2$, the receivers are totally disconnected (zero receivers connectivity). On the other hand, full receivers' connectivity (receivers' connectivity = 1) is achieved for $N = 10$ when the mesh density > $N\log N/2$. At $N = 15$, we achieve almost connected receivers when the mesh density is slightly greater than $N\log N/2$. While at $N = 20$, we achieve 50 % receivers' connectivity when the mesh density ≈ $N\log N/2$. Our results, although for small *N* values, matches the earlier asymptotic results of *Erdös* and *Rényi* [Erd59].

Figure 7.5 illustrates another interesting feature concerning the receivers' connectivity with respect to the average degree of the communication graph. We observe that for all values of *N*, the receivers are totally disconnected (zero connected receivers) when the average mesh degree < $ln(N)$. At $N = 10$, we obtain fully connected receivers (receivers connectivity = 1) when the average mesh degree is slightly greater than *ln*(*N*). While at *N* = 15 receivers are nearly connected when the average mesh degree ≈ *ln*(*N*), and at *N* = 20 the receivers are 50% connected when the average mesh degree tends to *ln*(*N*). These results match previous work in the theory of random graph [Alb02] concerning graph connectivity, and thus validate the similar behavior of our *RRG* model.

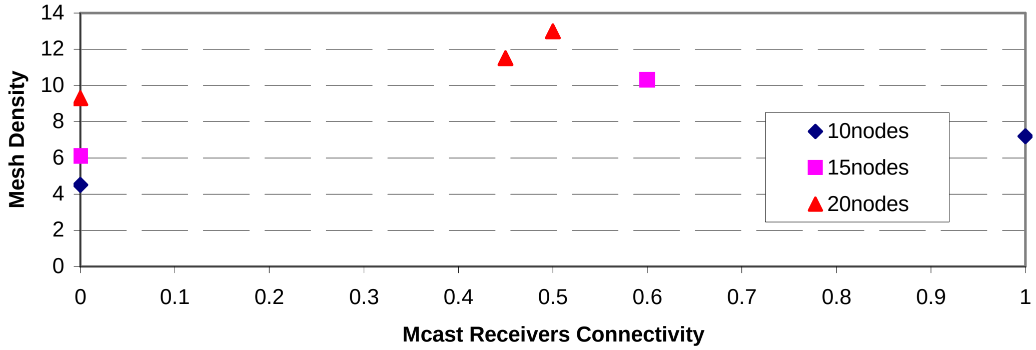


Figure 7.4 Small Size Graph: Multicast Receivers Connectivity versus Mesh Density

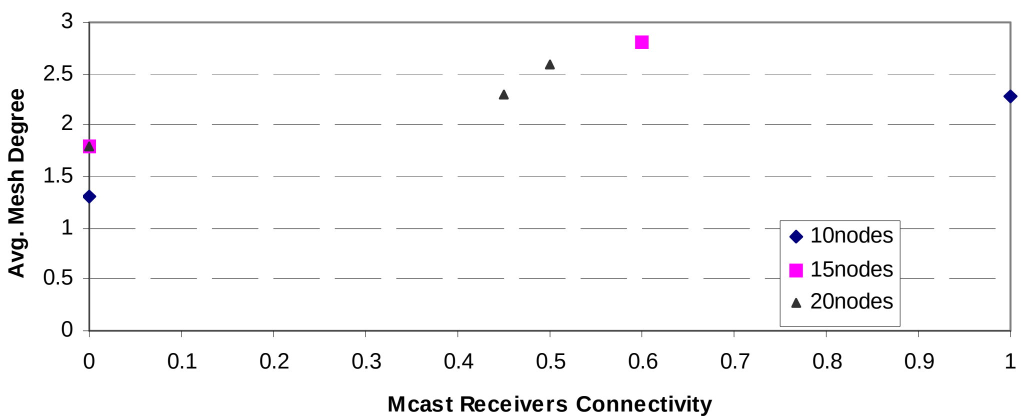


Figure 7.5 Small Size Graph: Multicast Receivers Connectivity versus Average Mesh Degree

In Figure 7.6 and 7.7, we study the connectedness of each multicast receiver in the group in terms of the number of paths connecting this receiver to the source. We study it as a function of the average edge probability; meanwhile we observe the receivers' connectivity to see if it is influenced with the change in the receivers' connectedness value. In Figure 7.6, it is clear that at *N* = 10 (the case of a multicast group consisting only of 1 receiver) the receiver's connectedness shows an increase until an average edge probability ≈ 0.7 then it decreases afterwards. This is due to the increase in communication graph density at average edge probability interval that includes 0.7, see

Figure 7.2. Although more connectedness is provided with denser graphs, the connectivity of the multicast group is not affected and it always exhibits a constant behavior starting from average edge probability 0.5 where it tends to 1.

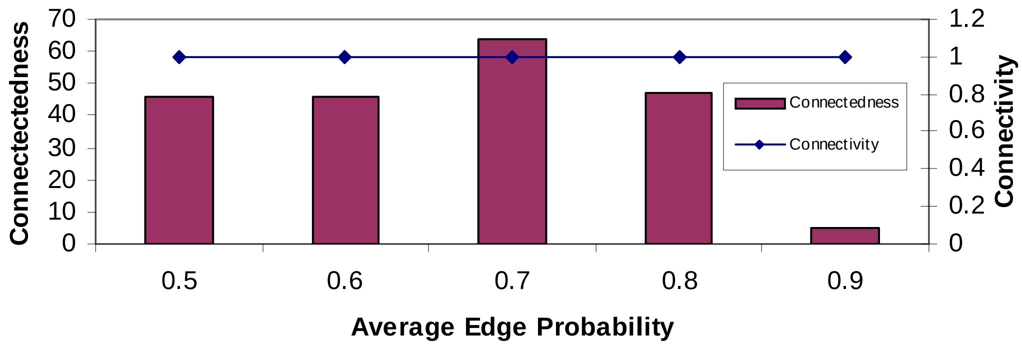


Figure 7.6 10-Node Graph: Average Edge Probability versus Receiver Connectedness and Connectivity

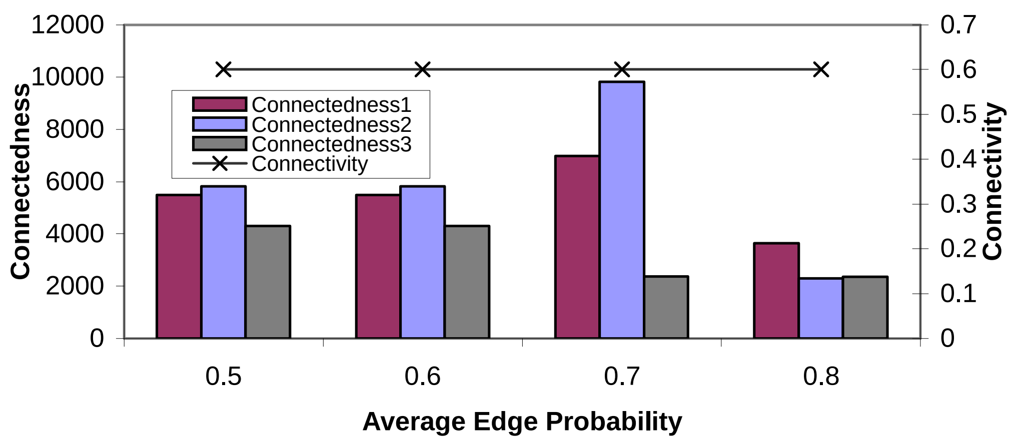


Figure 7.7 15-Node Graph: Average Edge Probability versus Receivers Connectedness and Connectivity

Figure 7.7, studies the connectedness of each receiver for N = 15 (the case of a multicast group consisting of 3 receivers), the same above behavior takes place among the 3 receivers. At the same time the increase in each receiver connectedness does not influence the connectivity of the multicast group, where it always exhibits a constant behavior starting from average edge probability 0.5. Thus, we notice that we can reach the same multicast group connectivity with less number of paths in the graph, or in other words with less dense graph in terms of more optimum size.

In general, it is noticed in Figure 7.6 and 7.7 that the same multicast group connectivity can be achieved through less dense communication graph. This is because the higher edge probability in *RRG* indicates the construction of more qualitative edges, implying less dense graph. Thus, the achieved optimization is in terms of providing reliable connectivity with minimum possible number of paths.

In Figure 7.8, we analyze the connectivity of large-scale communication graphs in terms of covering all the receivers' nodes. The evolution of the multicast receivers connectivity with different average edge probability takes the same behavior as small size communication graph. We notice the occurrence of a sharp phase transition at a critical probability or a crossover point equal 0.6. Zero connectivity is achieved if the average edge probability is below 0.6, while a phase transition to 100% connectivity takes place at an average edge probability equal 0.6. There is an obvious difference between these large-scale graphs and small size graphs (shown in Figure 7.1), where the sharp transition takes place from the zero connectivity to receivers connectivity equal 1 for all values of *N*. This transition behavior also provides a stable connectivity for average edge probability > 0.6.

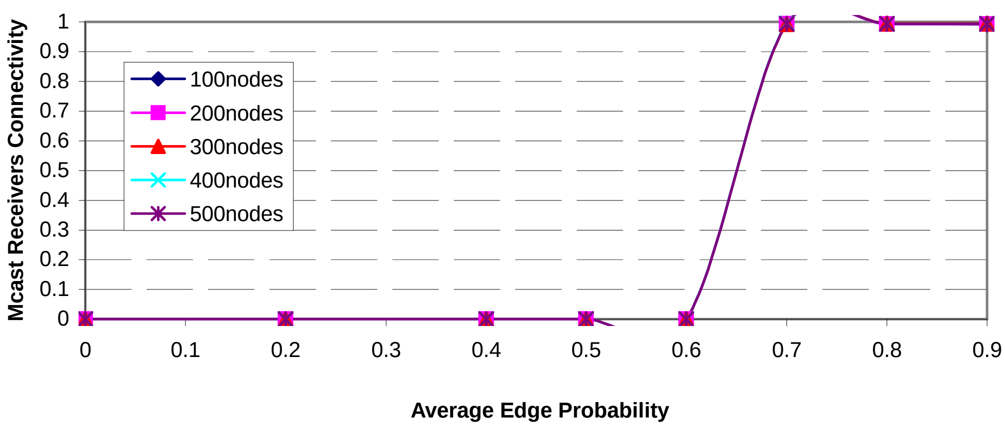


Figure 7.8 Large Scale Graph: Average Edge Probability versus Multicast Receivers Connectivity

The transition from zero connectivity to 100% connectivity for all values of *N* is not always satisfied in small size graph, since large graph size provides more possibility to cover all the receivers. We also observe a lag in the crossover point, from 0.4 to 0.6, compared to small size graphs, due to the criteria influencing $\boldsymbol{p}_{i,j}$ (t). In fact, the interference increase in large-scale graphs decreases the chances for qualitative links to exist. In other words, the edges' existence takes place based on the required constraints characterizing our *RRG* model, as mentioned in Section 7.3.3, which are satisfied at higher average edge probability compared to small size graph and thus causing this lag in phase transition.

The mesh density is illustrated in Figure 7.9, where a phase transition also arises at the same crossover point (0.6). When the average edge probability is below 0.6, a zero edge existence property takes place, translating the lack of connectivity in Figure 7.8 below this crossover point. Then the edges' existence begins at an average edge probability > 0.6 allowing the receivers' connectivity starting from this crossover point, see Figure 7.8. We notice that the mesh density exhibits different levels after the crossover point due to the different values of *N*, where it increases proportionally with *N*.

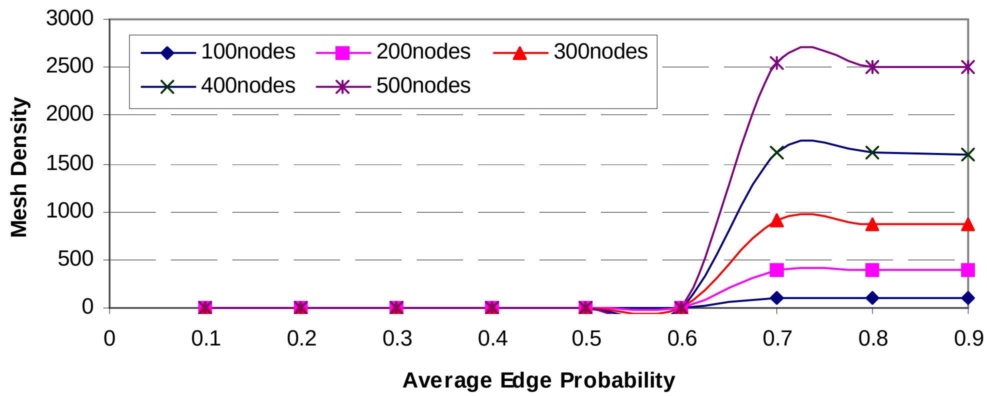


Figure 7.9 Large Scale Graph: Average Edge Probability versus Mesh Desnity

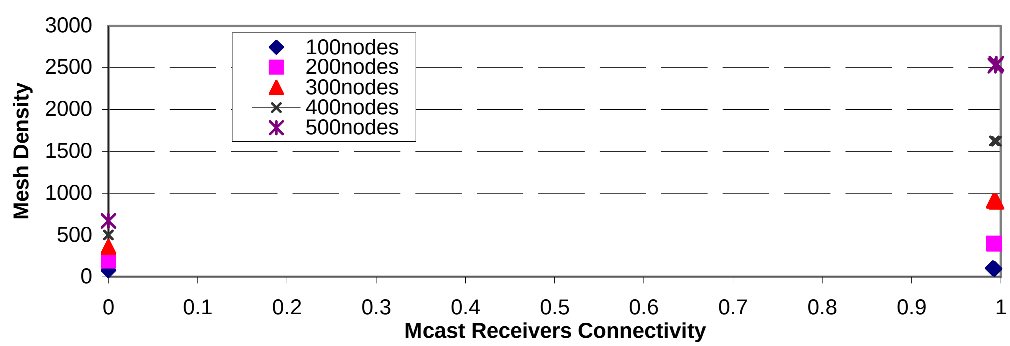


Figure 7.10 Large Scale Graph: Multicast Receivers Connectivity versus Mesh Density

The mesh density does not achieve a stable state after the crossover point; however it exhibits a slight decrease indicating the density decrease at higher average edge probability. This takes place for all values of *N*, however, it is not clear at *N* = 100 and 200 due to the large difference in scale. The same previous justification for small size graph explains this inclination behavior, where at higher average edge probability the density in terms of the number of edges decreases while the connectivity is not affected (see Figure 7.8) reflecting the communication graph robustness even at less dense network.

In Figure 7.10 and 7.11, we investigate our large-scale graphs evolution with respect to some asymptotic results from the theory of random graph. Figure 7.10, illustrates the receivers' connectivity as a function of the communication graph density, where we achieve 100% receivers' connectivity when the mesh density > *NlogN* /2 for nearly all values of *N*, and zero receivers' connectivity is achieved when the mesh density < *NlogN* /2.

The receivers' connectivity as a function of the average degree of the communication graph is given in Figure 7.11. It is noticed that, the receivers are totally connected if the average mesh degree > *ln*(*N*), otherwise they exhibit a zero connectivity. This behavior takes place at nearly all values of *N*.

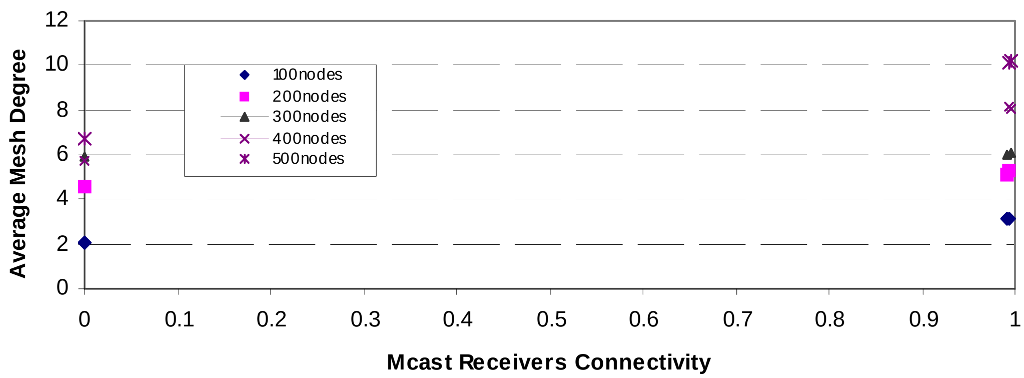


Figure 7.11 Large Scale Graph: Multicast Receivers Connectivity versus Average Mesh Degree

Our results in Figure 7.10 and 7.11 confirm our previous results for small size graphs in Figure 7.4 and Figure 7.5, where both results coincide with early asymptotic results in random graph theory especially for large values of *N* and prove that the *RRG* model exhibits the same random graphs characteristics.

7.6 Summary and Discussion

As mentioned earlier, our investigation focuses on the mesh structure constructed by the *SRMP* as a mean of connecting the multicast group members and providing reliable communication. In this context, we modeled the mesh structure as a communication graph and we develop the *RRG* model. Throughout our study, we observed that the *RRG* model exhibits the same features of random graphs while it attempts to extend the idea behind the edge existence probability, which is the base of any random graph, in a more useful mean. It aims at modeling a realistic radio environment or more precisely an ad hoc network environment, emphasizing our routing protocol (*SRMP*) behavior and basic features.

It is noticed from our results that some properties exhibit a sharp phase transition at a certain critical probability, thus confirming the behavior similarity between *RRG* and traditional random graphs. We defined three first order properties in Section 7.4 and we noticed from our results that these properties exhibit a phase transition. This matches earlier results from the random graph theory [Bol01]. *Property 1* shows a phase transition in Figure 7.1 for $N = 10$ and in Figure 7.8 for all values of N. *Property 2* exhibits a phase transition for small and large network's size, which is clear in Figure 7.2 and Figure 7.9 respectively. *Property 3* is tested for small size network ($N = 10, 15$) and it shows a phase transition, see Figure 7.6 and 7.7. This property is satisfied starting from critical edge probability equal to 0.5, otherwise it is not satisfied. Also, it does not keep a steady state after the transition at this critical probability; we consider that the transition takes place from non-satisfaction of the property to its satisfaction starting from the critical probability.

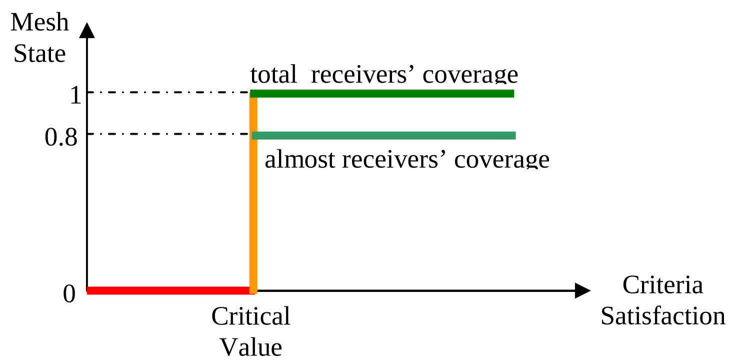


Figure 7.12 Mesh State based on Criteria Satisfaction

From our study we conclude that there is a critical average edge probability for the construction of a reliable mesh covering the multicast receivers, below which no communication or a poor communication might be achieved. Actually, this critical probability is mapped in the context of *SRMP* as the criteria in selecting the mesh members (Forwarding Group "*FG*" nodes). The selection criteria should have a certain level of satisfaction between nodes' pairs on the mesh in order to allow reliable communication; otherwise no communication can be achieved. We can say that the level of satisfaction of these criteria most probably causes an abrupt change in the mesh state from non-covering multicast receivers to totally or nearly covering the multicast receivers. This is expressed in Figure 7.12.

Some interesting properties are also discovered, which can help us to parameterize the mesh size in terms of the number of edges/links as a function of the number of nodes *N*. As shown in the above results, receivers' are almost connected if the number of edges constituting the connex part (including the source) of the mesh is greater than $N \log N/2$, as well as if the average mesh degree is greater than ln(*N*). We also noticed that as the average edge probability increases, the mesh density decreases. The decrease rate is small for some values of *N*, which is an important behavior in SRMP. In this context, this is considered a decrease in the number of links constituting the mesh, which results in an increase in the selection criteria satisfaction level. However, the connectivity of the multicast receivers remains always stable.

Accordingly, the level of satisfaction of our *FG* nodes selection criteria should be wisely considered to obtain a compromise between the receivers' connectivity and the minimum possible mesh size, through studying the appropriate thresholds set and their impact on the mesh size and connectivity. Our goal is to keep the same connectivity level with the minimum possible resources' utilization, delay, and network's load aiming to improve the performance of *SRMP*.

A future work would be to consider the continuity of this model, through considering different values of ***t***, such that ***t*** value continuously varies in the interval $[\boldsymbol{t_0}, \boldsymbol{t_{max}}]$.

CHAPTER 8 CONCLUSION

8.1 Contributions

Wireless mobile ad hoc networks present difficult challenges to unicast and multicast routing protocols design. Routing protocols in these networks must construct and maintain multihop routes effectively and efficiently. The major challenges to be addressed in any routing protocol design are mainly flexibility, availability, adaptability, robustness and power conservation. We have chosen to work with on-demand routing protocols as they are well suited to mobile ad hoc networks, especially when the mobility rate is high.

The main lessons which we have learned from our studies during the thesis are:

- The shortest path which is mostly used as a base criterion in routes establishment does not always provide the optimal routes in a dynamic network as ad hoc network. Other important criteria should be considered (as path stability, power efficiency, and links quality). Hence, the choice of the routing path should be adaptive to the dynamic environment while considering these factors.
- Efficient utilization of power resources is a primary reason of good routing performances. Moreover, providing qualitative routes increases robustness to mobility and fading.
- There is a need for considering the impact of the different mobility models on the routing performance evaluation. It is also important to choose the appropriate mobility model, reflecting the applications' need.

8.1.1 Unicast Routing

In this part, we mainly focused on energy efficient routing in MANETs. In this context, we proposed EC-DSR protocol. Our proposition investigates the unicast routing problems, considering a distinctive approach that addresses the energy conserving issues and exploits the quality of connectivity.

We conducted a performance evaluation of EC-DSR compared to DSR protocol, as it is the base protocol in implementing our proposition. We carried out our performance analysis in diverse network configurations, and diverse mobility types and models. Our obtained results show a significant enhancement on EC-DSR control packets utilization, and robustness against mobility. We also obtained an enhanced routing efficiency, compared to DSR, in scalable networks with more traffic load.

We investigated the effect of group mobility models on EC-DSR simulation performance compared to the popularly used Random Waypoint model. We obtained better results for group mobility models especially in large networks.

8.1.2 Multicast Routing

In this part, we focused on one critical issue in MANETs that is multicast routing. The drawbacks of existing multicast mechanisms involve the necessity of designing new powerful schemes. In this context, we proposed SRMP as a novel multicast routing protocol. It is a mesh-based protocol, providing robustness to hosts mobility and richer connectivity. During the mesh construction, SRMP utilizes efficient selection criteria for nodes selection through employing four selection metrics. SRMP guarantees loop freedom and fewer overheads in maintaining next hop information, due to applying the source route concept.

We fulfilled a vast performance evaluation for SRMP, invoking a variety of mobility and communication scenarios, various network sizes and configurations, different multicast group compositions and different mobility models providing realistic conditions. A performance comparison study is also carried out with ODMRP and ADMR protocols.

We highlight the following conclusions from our obtained results:

- Even though the three protocols share an on-demand behavior, the difference in each protocol strategy leads to performance differentials. We also demonstrated that even though SRMP and ODMRP share the mesh-based approach, the difference in each protocol strategy in terms of route discovery and maintenance leads to different protocols' performance.
- SRMP shows a significant decrease in control overhead and it is more efficient in terms of energy consumption.
- In larger network configuration, SRMP exhibits an improved delivery ratio, compared to ODMRP and ADMR, starting from intermediate mobility.

- SRMP results in a negligible size of data packets re-transmission at the MAC layer, compared to ODMRP and ADMR, as it provides connectivity quality during its mesh construction. Thus it is more efficient in bandwidth utilization, which is a necessary requirement for an efficient multicast routing protocol.
- In highly dynamic network cases, SRMP does not show remarkable results in terms of delivery ratio and delay compared to ODMRP and ADMR. Moreover, in scalable networks configurations SRMP performance enhancements mainly concern the energy consumption.
- SRMP shows better performance with group mobility models, when the number of multicast groups increases.

We investigated the impact of thresholds variations during the mesh nodes selection. From the obtained results, we conclude that different thresholds' values influence the connectivity quality estimate and hence show a significant impact on SRMP performance.

We also developed the reactive random graph (RRG) model to analyze the reliability of the SRMP constructed mesh. Our analysis results prove that there is a critical average link probability for reliable mesh construction. This implies that the selection criteria should have a certain level of satisfaction between nodes' pair in order to allow reliable communication; otherwise no communication can be achieved.

8.2 Perspectives

The richness of the treated themes makes us elaborate a certain number of future research directions, some are short terms and others aim to provide more wide investigations.

Concerning the routing performance part, SRMP still needs some investigations at this level. More study for SRMP behavior with different multicast group compositions is needed. SRMP routing cache still needs some investigations, concerning its size and its storage and access mechanisms. The behavior of some performance metrics need to be studied at the receiver side, rather than assuming the average behavior in all our previous work. More traffic scenarios should be tested, considering large number of sources and studying the effect of sources and receivers pruning. A mathematical model would be interesting to validate the performance results. It is also important to develop an adaptive mechanism that allows the thresholds' adjustment as a function of the mobility type and network configuration, and to fulfil the continuity of the RRG.

We also propose the following perspectives as a mean of providing more investigations in this area of study:

- Evaluating the routing performance using real life mobility traces;

- Provide the simulator with an actual multicast application environment for testing SRMP routing performance;
- Investigating the interaction between MAC and routing layers, and its effect on the routing protocols performance;
- Studying the effect of different applications and transport protocols on the routing performance;
- Studying the impact of interference on the reception of data packets at the receivers;
- Introducing mobility models with obstacles, emulating the wireless medium constraints;
- Securing the multicast session;
- Load balancing on the mesh paths;
- Quality of service provisioning.

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APPENDIX A

Network Simulator*2* (*ns*-2) is a discrete event simulator targeted at networking research. It provides substantial support for simulation of TCP, multicast routing, and other protocols over conventional networks. It also supports accurately simulating the physical aspects of multi-hop wireless networks and the MAC protocols needed in such environment. The simulator is written in C++ and a script language called OTcl (Object Tool command language). OTcl is used as an interpreter towards the user, where the user writes an OTcl script to define the network (number of nodes, links, topography, used protocol, network traffic/ sources and destinations, traffic types, mobility rate, mobility patterns, nodes' transmission range….., etc). This script is then used by ns during the simulation. The result of simulation is an output file named (trace file) that can be used for data processing (calculation of delay, throughput, packets' drop, links failure, …etc). To visualize the simulation, another output file is generated named (nam file), this file is run through a Network Animator (NAM) in ns.

A.1 Mobile Nodes Implementations

Mobile nodes in *ns*-2 make use of routing agents for the purpose of calculating routes to other nodes in the network. Figure A.1 shows the functional architecture of a wireless multicast mobile node under *ns*-2, which we developed during our implementation to SRMP. The *entry_* point forces all packets received by the node to be handled down to the routing agent (*rtr_agent*). This agent classifies each packet according to its type (unicast or multicast) then forwards it whether to the unicast agent (*uni_agent*) or the multicast agent (*srmp_agent*). SRMP agent checks every data packet, handling all packets destined to it to the port (*mcast_dmux*). Otherwise, it forwards the data packet on the link to the next hop towards the destined multicast receivers. The port (*rt_port*) points to a null agent, since the packet has already been processed by the routing agent.

A.2 Simulation Model

In order to make fair comparison, it is critical to challenge the protocol with identical loads and environmental conditions. Each simulation under *ns*-2 accepts two scenario files as input, a movement scenario file describing nodes' movements and a traffic scenario file describing the type of traffic that is generated through the network.

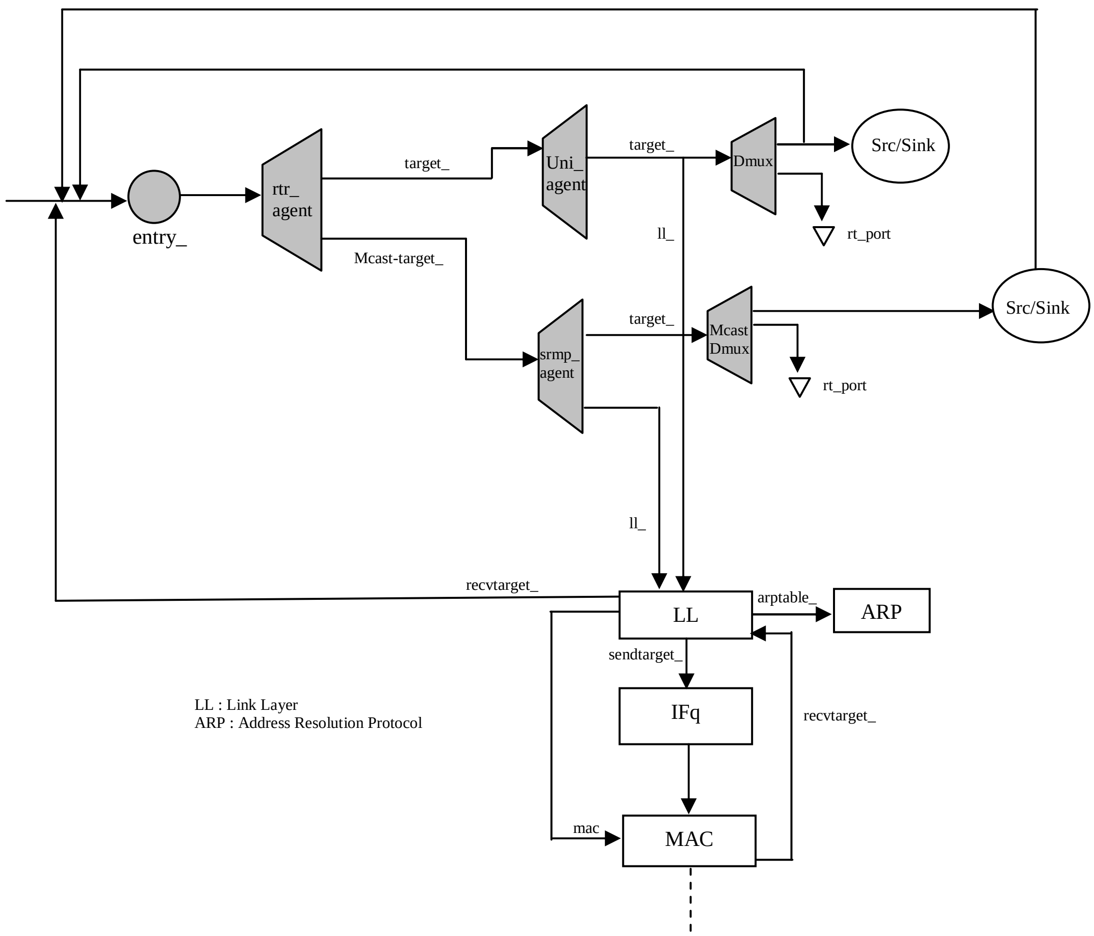

Figure A.1 Wireless Multicast Mobile Node

A traffic scenario file describes the sequence of packets originated by each traffic source node, the destination(s) for each source originating data, the time at which each change in packet origination occurs, and the multicast group composition in case of multicast routing. The main transport agents implemented in *ns-2* are the UDP and the TCP agents. In our simulations, we choose constant bit rate (CBR) traffic, generated over UDP agents. While we do not use TCP as it offers a conforming load to the network, where it changes the times at which it sends packets based on its perception of the network's ability to carry packets. As a result, the time at which each data packet is originated by its sender and the position of the node while sending would differ between the protocols, preventing a direct comparison between them.

The movement scenario files represent the movement model for the running simulations under ns-2, describing the movement of each node and the time at which each change in movement occurs. This provides the nodes' mobility model or pattern of movements in the simulated ad hoc network. Random Way Point (RWP) model is the only mobility model that exists under *ns-2*, and we integrated the other mobility models which we used during our performance studies.

APPENDIX B

Random graph theory studies the properties of the probability space associated with graphs with N nodes as $N \to \infty$. *Erdös* and *Rényi* used the definition that almost every graph has a property $\boldsymbol{Q}$ if the probability of having $\boldsymbol{Q}$ approaches 1 as $N \to \infty$. Thus, a typical element of the probability space has a property $\boldsymbol{Q}$ when the probability that a random graph of N vertices has $\boldsymbol{Q}$ tends to 1 as $N \to \infty$ [Bol01].

The $G_{N,M}$ model defines a distribution for a sample space consisting of graphs with N vertices and M edges, forming a probability space in which every graph G realization is equiprobable. Denote H as any graph of N vertices and M edges, $P(G = H) = 1/{}_N C_M$. While, the $G_{N,P}$ model defines a distribution for a sample space of graphs with N vertices. Each of the ${}_N C_2$ possible edges has an independent probability P of existing. and m edges this probability is $P^m(1-P)^{M-m}$, where $M = N(N-1)/2$.

B.1 Random Graph Properties

The greatest discovery of *Erdös* and *Rényi* was that many important properties of random graphs appear quite suddenly. That is, at a given probability either almost every graph has some property $\boldsymbol{Q}$ (e.g., every pair of nodes is connected by a path of consecutive edges) or, conversely, almost no graph has it [Bol01]. The transition from a property's being very unlikely to it being very likely is usually a swift. For many such properties there is a critical probability $P_C(N)$. If $P(N)$ grows more slowly than $P_C(N)$ as $N \to \infty$, then almost every graph with connection probability $P(N)$ fail to have $\boldsymbol{Q}$. If $P(N)$ grows somewhat faster than $P_C(N)$, then almost every graph has the property $\boldsymbol{Q}$. Among the questions addressed in this context have direct relevance to the understanding of complex networks, such as: Is a typical graph connected? Does it contain a triangle of connected nodes? How does its diameter depend on its size?

B.1.1 Percolation Theory

Percolation theory deals with fluid flow in random media. It studies the formation and structure of clusters in a large lattice, if the cluster (connected area) goes from top to down, it is said that the system has "percolated". At a critical probability p_c, called the *percolation threshold*, a percolating (infinite) cluster of nodes connected by edges appears. Such a transition usually allows an important transformation in the system that is modeled, this transformation is known as a **phase transition**.

B.1.2 Phase Transition in the Properties of Random Graphs

Some properties of random graphs show interesting behavior around the transition point, which is the characteristic of phase transition [Alb02] explored from the percolation theory [Stu92]. *Erdös* and *Rényi* described the asymptotic behavior of the phase transition for random graphs with *N* sufficiently large; the following is a corollary of their result [Fra95];

Corollary 1: **P (G** is connected**)** = 0 if E < (NlogN)/2
and **P (G** is connected**)** = 1 if E > *(NlogN)/2*

Pösa used this result to study the property of Hamiltonian cycles formation in random graphs, given that $N \rightarrow \infty$. Theorem 1, illustrates the result of his study, proved in [Van98].

***Theorem 1: P (G** contains Hamiltonian cycle**)** = 1 if E = cNlogN, given c sufficiently large.*

B.2 Random Graphs in Modeling MANETs

Recently, mathematical models of random graphs and percolation theory have been explored as a source of inspiration for designing solutions with in MANETs. Mathematical models of random communication graphs are explored in [Dow01] and are used to validate scientific-computing techniques for Ad hoc networks and Distributed Sensor Networks (*DSNs*). The connectivity property is studied for both purely ad hoc networks and hybrid networks in [Dou02], evaluating the probability $P_c(x)$ that two random nodes *A* and *B*, whose Euclidean distance is denoted by $d(A, B) = x$, are connected to each other as a function of the nodes density, radius of transmission and the distance *x*.

Random graph theory is also used to provide a handle on the design and analysis of ad hoc wireless networks. An admission control and power control schemes are proposed in [Chia01] based on the evolution of ad hoc networks. While a scalable analysis of ad hoc network is studied in [Far02], regarding the properties of random network topology, to provide a solution for the problem of the appropriate transmission range design.

The percolation of broadcast in a multihop radio network is early studied in [Che89], where they examine the relation between the transmission range, nodes' density, and connectivity of ad hoc networks in the context of "broadcast percolation". While [Haa02] studied the idea of probabilistic flooding in ad hoc networks to eliminate unnecessary propagation of many routing messages. [Sas02] explored the phase transition phenomena observed in percolation theory and random graphs, as a basis for defining probabilistic flooding in MANETs. Some properties of ad hoc networks exhibiting phase transition behavior are also discussed in [Kri01, Spen87], proving that every first order graph property (described in Boolean logic) exhibits a zero-one law.

Due to the complex routing problem, there are few contributions using random graphs to analyse the routing characteristics. An analysis of ad hoc routing performance is proposed in [Jac99] using random graph models. The goal is to compare reactive and proactive unicast protocols (using DSR and OLSR as examples), via comparing the route discovery and route non-optimality overhead in reactive scheme with the periodic control traffic overhead in proactive scheme.